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AVAILABILITY OF FERTILIZER AND SOIL PHOSPHORUS TO GRAIN CROPS, AND THE EFFECT OF PLACEMENT AND RATE OF APPLICATION ON PHOSPHORUS UPTAKE[1]

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It is now about thirty years since Hevesy introduced the application of radioactive isotopes as indicators in plant studies (10). However, only within the last few years has it been generally appreciated that radio isotopes provide an invaluable tool for investigating the availability of plant nutrients under field conditions. While a number of isotopes have been used, the economic importance of phosphate fertilizer and the relative ease of handling P^{32} have resulted in particular attention being paid to phosphorus. Numerous examples of the use of P^{32} have appeared in the few years that have elapsed since the first field experiments were carried out by the Saskatchewan group in the season of 1946 (16, 17). The experiments reported have covered such diverse topics as utilization of various phosphatic fertilizers by different crops at various stages of growth, grown on different types of soil, with methods of placement, various rates of application and various times of application (18, 19, 6, 20, 4, 5, 3, 8, 13). The expansion of this work is perhaps best illustrated by the fact that the United States alone used 30 curies P^{32} for fertilizer experiments last year, whereas five years ago the first field experiment was done with less than 1 millicurie P^{32}.

It may be desirable to point out that the validity of results in using tracer phosphorus depends upon the P^{32} being in the same valence state, and chemical form, as the fertilizer material being studied (17). It was also pointed out in the paper cited that the occurrence of isotope exchange would not invalidate the use of the tracer technique in such studies.

During the 1950 season the availability of phosphate fertilizers of analysis 0–20–0 (standard superphosphate) and 11–48–0 (mono-ammonium phosphate) to wheat, oats and barley was investigated. The effect of varying the rate of application of 11–48–0 from 0 to 96 pounds P_2O_5 per acre on the uptake of fertilizer by wheat plants was investigated for two soils and placement experiments were done for three different soils. Observations on radiation effects were also made.

[1] Contribution from Departments of Chemistry and Soils, University of Saskatchewan. Presented by J. W. T. Spinks at International Congress of Pure and Applied Chemistry, New York, August, 1951.
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[3] Formerly Research Associate, now Assistant Professor of Chemistry.
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[5] Professor of Chemistry and Dean of College of Graduate Studies.

TABLE 1.—THE EFFECT OF SUPERPHOSPHATE AND AMMONIUM PHOSPHATE ON INDIVIDUAL CROPS

P_2O_5 = 24 lb./acre

Fertilizer Treatment	Grain yield bu./acre	Plant wt. lb./acre in hundreds	Phosphate taken up			
			Total P_2O_5 lb./acre	Soil P_2O_5 lb./acre	Fert. P_2O_5 lb./acre	% Fert. P_2O_5 used
			Barley (*Titan*)			
Check	30.2	43.0	22.5	22.5	0	0
0–20–0	34.6	53.7	28.0	20.0	8.0	33.4
11–48–0	34.6	56.4	28.0	19.4	8.7	36.2
L.S.D. (0.05)	N.S.	8.2	5.0	N.S.	N.S.	
			Barley (*Montcalm*)			
Check	39.6	51.7	25.1	25.1	0	0
0–20–0	42.8	53.7	25.8	19.7	6.1	25.7
11–48–0	44.5	57.0	26.2	19.3	6.9	28.9
L.S.D. (0.05)	N.S.	N.S.	N.S.	3.3	N.S.	
			Oats (*Exeter*)			
Check	72.3	79.1	28.2	28.2	0	0
0–20–0	76.1	85.4	30.4	23.4	7.1	29.5
11–48–0	79.4	82.0	27.2	19.6	7.6	31.8
L.S.D. (0.05)	N.S.	N.S.	N.S.	3.6	N.S.	
			Wheat (*Thatcher*)			
Check	23.2	38.5	23.6	23.6	0	0
0–20–0	28.0	47.6	30.1	23.9	6.2	25.8
11–48–0	32.5	52.9	32.1	24.8	7.2	30.5
L.S.D (0.05)	5.6	7.8	5.7	N.S.	0.8	

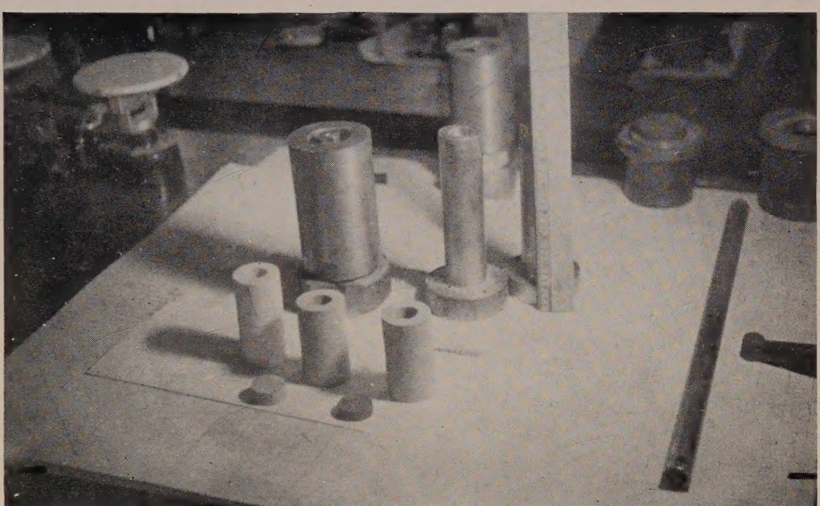

FIGURE 1. Hollow cylinders and briquets of pressed plant material and, in background, steel moulding cylinders for use in carver press.

MATERIALS AND METHODS

A part of the ammonium phosphate was prepared by adding P^{32} in the form of H_3PO_4 to an aqueous solution of mono-ammonium phosphate and evaporating to dryness at less than 45° C. The remainder of the mono-ammonium phosphate and all the standard superphosphate were obtained from the United States Department of Agriculture*.

The fertilizer and grain were sown together with a Kemp V belt plot seeder. Except for the placement experiments, fertilizer and seed were at the same level. Each treatment plot consisted of three rows, all being given the same fertilizer treatment but only the centre row being treated with radioactive fertilizer. The rows were 16.5 feet long, the centre 12 feet being harvested. Six replicates were used in a randomized block arrangement.

Experimental plots were distributed from Kyle, approximately 150 miles southwest of Saskatoon, to Melfort, approximately 150 miles northeast of Saskatoon.

The location of the plots and their soil types are:

1. Kyle	Sceptre Heavy Clay**	(Brown lacustrine soil)
2. Birsay	Haverhill Loam	(Brown soil on glacial till)
3. Watson	Yorkton Loam	(Black calcareous soil on till)
4. Birch Hills	Melfort Silty Clay	(Thick black lacustrine soil)
5. Melfort	Melfort Silty Clay	(Thick black lacustrine soil).

Moisture conditions, excepting at Birsay (placement experiment) were quite good, but, owing to a late spring and a cool summer, harvesting was approximately two weeks later than usual. Frost damage was noticeable in only one experiment, a study of rates of application of fertilizer at Watson. However, damage was not serious enough to invalidate the results.

Unless otherwise specified, the crop grown was Thatcher wheat and the phosphate fertilizer was applied at the rate of 24 pounds of P_2O_5 per acre. The level of activity was approximately 100 microcuries P^{32} per gram P^{31}. For analysis, the above-ground plots were harvested, ground and wet ashed by the method of Brenner and Harris (2). Determinations of phosphorus were made by the phosphomolybdate blue reaction using hydrazine as a reducing agent (14). P^{32} was determined by counting the dried and ground plant material in either the form of a briquet or of a hollow cylinder (11). (*See also Figure 1*). By using as a standard a briquet or cylinder made from an aliquot of the original labelled fertilizer mixed with inactive plant paterial, the uptake of fertilizer is very simply and directly measured. Knowing the total phosphorus uptake from ordinary chemical analysis, the uptake of soil phosphorus is easily obtained by the difference. It is scarcely necessary to point out that this could not be done without tracers.

Three distinctive methods for determining P^{32} in plant material have been used in these experiments. The first requires conversion of phosphorus in plants to a pure chemical form such as magnesium pyrophosphate and the use of an end-window counter to count the solid precipitate.

* We are grateful to the U.S.D.A. for their generosity in supplying this material.

** Full descriptions of soil types may be found in Saskatchewan Soil Survey Report No. 12, University of Saskatchewan, Saskatoon.

The second method is by dissolving the material and counting it in solution with a solution counter. The third method involves grinding dried plant material and compressing it into a briquet to be counted with an end-window counter, or compressing it into a hollow cylinder which is placed around a thin-wall counter tube and counted directly. This last method has proven to be the most convenient and rapid for the large number of plant samples analysed in the authors' experiments.

RESULTS

Crops and Varieties

The availability of phosphorus from mono-ammonium phosphate and standard superphosphate was determined for Exeter oats, Titan barley, Montcalm barley and Thatcher wheat. These results are given in Tables 1, 2 and 3.

As shown in Table 1, the only significant increase in grain yield was from ammonium phosphate on Thatcher wheat. A significant increase in plant weight was obtained for Titan barley and Thatcher wheat from both

Table 2.—Effect of fertilizer treatment
(Mean of 4 crops at maturity)

Treatment	Grain yield lb./acre in hundreds	Plant wt. lb./acre in hundreds	Phosphate taken up		
			Total P_2O_5 lb./acre	Soil P_2O_5 lb./acre	Fert. P_2O_5 lb./acre
Check	18.1	53.0	24.8	24.8	0
0–20–0	20.0	60.1	28.6	21.7	6.8
11–48–0	21.1	62.0	28.4	20.8	7.6
L.S.D. (0.05)	1.4	3.5	2.0	2.1	0.5

Table 3.—Effect of crop on phosphorus uptake
(Mean of both fertilizers)

Crop	Total P_2O_5 lb./acre	Soil P_2O_5 lb./acre	Fert. P_2O_5 lb./acre	Ratio $\frac{\text{Soil } P_2O_5}{\text{Fert. } P_2O_5}$
	Birch Hills—1950			
Exeter oats	28.8	21.5	7.3	3.10
Titan barley	28.1	19.7	8.4	2.43
Montcalm barley	26.1	19.5	6.5	3.08
Thatcher wheat	31.1	24.4	6.7	3.76
L.S.D. (0.05)	3.1	2.7	N.S.	0.80
	Birch Hills—1949			
Montcalm barley	28.4	19.5	8.9	2.24
Thatcher wheat	23.8	17.1	6.8	2.65
L.S.D. (0.05)	2.6	2.1	0.6	0.35

0–20–0 and 11–48–0. Total phosphorus uptake is also significantly higher for both fertilizers on Titan barley and Thatcher wheat, while soil phosphorus uptake is significantly lower for Montcalm barley and Exeter oats. The general trend indicates a more efficient utilization of phosphorus from 11–48–0 than from 0–20–0 and the uptake of phosphorus is significantly higher for Thatcher wheat (Table 1) and for all four crops when the data are combined as in Table 2.

Table 3 gives data for the seasons 1949 and 1950 showing the effect of crop on phosphorus uptake from the two phosphate fertilizers. Variations due to season are illustrated by the fact that Thatcher wheat had more total phosphorus than Montcalm barley in 1950, but less in 1949. Thatcher wheat also showed a greater uptake of soil phosphorus than the other crops in 1950 but less than Montcalm barley in 1949. These erratic results indicate a need for further data in regard to crops and varieties and their response to phosphate fertilizer.

Placement Experiments

A number of experiments were conducted on the effect of placing seed and fertilizer in different relative positions. A comparison was also made between 11–48–0 as granules and in powdered form for one of the fertilizer-seed placements. The placements were as follows:

1. Seed at 3″
2. 11–48–0 (granules) at 3″, seed at 3″
3. 11–48–0 (powder) at 3″, seed at 3″
4. 11–48–0 (granules) at 2″, seed at 3″ (This treatment at Kyle only)
5. Trench to 4.5″, seed at 3″
6. 11–48–0 (granules) at 4.5″, seed at 3″
7. Seed at 4.5″
8. 11–48–0 (granules) at 4.5″, seed at 4.5″.

This experiment was done at three locations, Kyle, Birsay and Melfort. The results are summarized in Tables 4, 5, 6 and 7.

The results obtained at Birsay (Table 4) were affected by a very dry season, as indicated by a maximum yield at 3.3 bushels per acre. Nevertheless, significant increases in yield were obtained and an interesting result is the very high percentage of the phosphorus in the plant which came from the fertilizer, although there was a very low recovery of the applied phosphorus as a result of poor growth. The high percentage of applied phosphorus in the plant tissue indicates that the availability of soil phosphorus has been decreased to a greater extent than fertilizer phosphorus by the dry season. The fact that trenching to a depth of 4.5 inches and seeding at 3 inches increased the yield significantly is difficult to explain. It may be a result of bringing moist soil in contact with the seed as a result of disturbing the soil and so improving germination.

At Kyle (Table 5) no significant differences appear at maturity except if the data are combined to show mean results of fertilized and unfertilized treatments. At Melfort (Table 6) significant increases in grain yield and plant weight are shown with the best yield secured from seed at 3 inches and fertilizer at 3 inches, as was the case at Kyle. The fertilizer phosphorus taken up is also greater at this depth and is significantly higher than where

TABLE 4.—FERTILIZER PLACEMENT—BIRSAY

Depth of Seed and Fertilizer	Grain yield bu./acre	Plant wt. lb./acre in hundreds	Phosphate taken up by plants				
			Total P_2O_5 lb./acre	Soil P_2O_5 lb./acre	Fert. P_2O_5 lb./acre	% recovery of applied P_2O_5	Fert. P_2O_5 as % of Total in plant
			First Harvest—July 7, 1950				
Seed 3″		1.90	0.81	0.81	0		0
Seed 3″, Fert. 3″		2.40	1.24	0.45	0.79	3.30	63.8
Seed 3″ Fert. 4.5″		3.93	1.73	0.60	1.13	4.71	65.2
Seed 3″ Trench 4.5″		2.70	0.87	0.87	0		0
Seed 4.5″		1.92	0.97	0.97	0		0
Seed 4.5″ Fert. 4.5″		2.68	1.37	0.51	0.85	3.58	61.9
L.S.D. (0.05)		1.36	0.62	0.46	N.S.		
			Final Harvest—August 20, 1950				
Seed 3″	1.41	2.37	0.77	0.77	0		0
Seed 3″ Fert. 3″	2.98	4.64	1.76	0.38	1.38	5.89	78.2
Seed 3″ Fert. 4.5″	2.29	3.42	1.23	0.30	0.93	3.89	75.6
Seed 3″ Trench 4.5″	3.35	4.73	1.52	1.52	0		0
Seed 4.5″	1.41	2.18	0.80	0.80	0		0
Seed 4.5″ Fert. 4.5″	1.76	2.56	0.96	0.37	0.59	2.47	61.3
L.S.D. (0.05)	1.17	1.49	0.59	0.40	N.S.		

TABLE 5—FERTILIZER PLACEMENT—KYLE

Depth of seed and fertilizer	Grain yield bu./acre	Plant wt. lb./acre in hundreds	Phosphate taken up by plants: Total P_2O_5 lb./acre	Soil P_2O_5 lb./acre	Fert. P_2O_5 lb./acre	% recovery of applied P_2O_5	Fert. P_2O_5 as % of total in plant
First Harvest—July 24, 1950							
Seed 3″		25.7	11.6	11.6	0		0
Seed 3″ Fert. 2″		25.7	13.7	10.2	3.5	14.7	25.6
Seed 3″ Fert. 3″		28.4	13.8	9.3	4.5	18.9	32.6
Seed 3″ Fert. 4.5″		27.2	12.2	8.2	4.2	17.8	34.4
Seed 3″ Trench 4.5″		23.2	10.7	10.7	0		0
Seed 4.5″		29.7	9.8	9.8	0		0
Seed 4.5″ Fert. 4.5″		23.6	11.7	7.9	3.8	15.8	32.5
L.S.D. (0.05)		4.6	1.1	1.8	0.7		
Final Harvest—September 7, 1950							
Seed 3″	33.8	44.7	23.6	23.6	0		0
Seed 3″ Fert. 2″	39.4	53.0	28.6	22.4	6.3	26.1	22.0
Seed 3″ Fert. 3″	43.4	63.1	26.3	18.8	7.5	31.0	28.6
Seed 3″ Fert. 4.5″	37.2	47.3	26.6	20.0	6.6	27.5	24.8
Seed 3″ Trench 4.5″	31.1	43.4	25.1	25.1	0		0
Seed 4.5″	30.1	43.8	22.4	22.4	0		0
Seed 4.5″ Fert. 4.5″	41.5	54.6	28.4	21.7	6.5	27.1	22.9
L.S.D. (0.05)	N.S.	N.S.	N.S.	N.S.	N.S.		
Mean unfertilized	32.0	44.0	23.7	23.7	0		
Mean fertilized	40.4	52.6	27.7	20.7	7.0		
L.S.D. (0.05)	4.0	4.8	1.9	2.5			

TABLE 6.—FERTILIZER PLACEMENT—MELFORT

Depth of seed and fertilizer	Grain yield bu./acre	Plant wt. lb./acre in hundreds	Phosphate taken up by plants				
			Total P_2O_5 lb./acre	Soil P_2O_5 lb./acre	Fert. P_2O_5 lb./acre	% recovery of applied P_2O_5	Fert. P_2O_5 as % of total in plant
First Harvest—July 16, 1950							
Seed 3″		17.1	7.6	7.6	0		0
Seed 3″ Fert. 3″		32.1	12.5	6.3	6.2	26.1	49.6
Seed 3″ Fert. 4.5″		27.8	12.7	7.7	5.0	20.9	39.4
Seed 3″ Trench 4.5″		18.5	9.3	9.3	0		0
Seed 4.5″		9.1	4.3	4.3	0		0
Seed 4.5″ Fert. 4.5″		24.1	11.7	6.7	5.0	20.7	42.8
L.S.D. (0.05)		2.9	1.2	1.2	0.7		
Final Harvest—September 9, 1950							
Seed 3″	34.0	42.7	22.1	22.1	0		0
Seed 3″ Fert. 3″	46.6	60.4	26.2	17.9	8.3	34.9	31.7
Seed 3″ Fert. 4.5″	43.4	54.8	25.0	17.3	7.7	32.1	30.8
Seed 3″ Trench 4.5″	33.8	42.3	21.3	21.3	0		0
Seed 4.5″	24.7	32.3	16.9	16.9	0		0
Seed 4.5″ Fert. 4.5″	41.5	51.9	23.9	16.9	7.0	29.3	29.3
L.S.D. (0.05)	5.1	6.1	3.4	3.5	1.1		

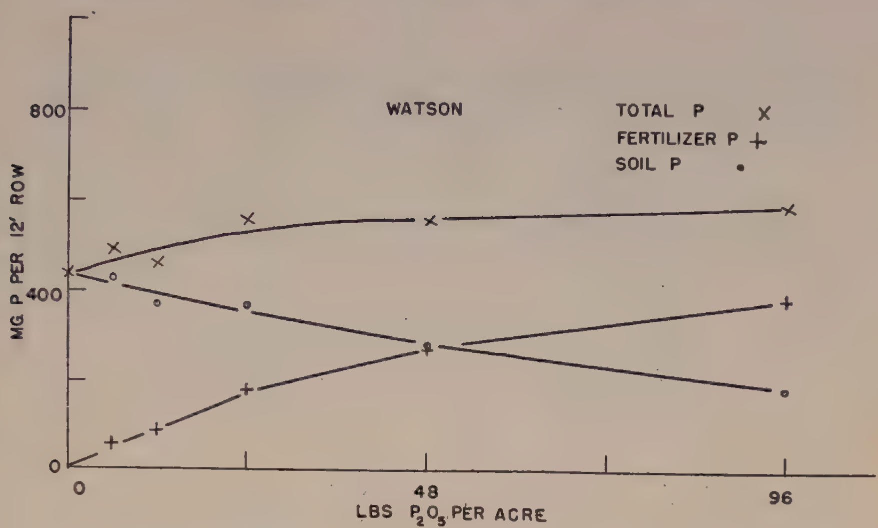

FIGURE 2. Relationship between total phosphorus in plant and phosphorus uptake from soil and fertilizer, as influenced by rate of application at Watson, Saskatchewan, 1950.

both seed and fertilizer are placed at 4.5 inches. At Melfort deep seeding was quite detrimental as indicated by a drop in yield of nearly 10 bushels where the seed was placed at a depth of 4.5 inches compared to seeding at 3 inches. A trend toward reduction in the uptake of soil phosphorus due to the application of fertilizer is indicated in all experiments. The data for all three locations are summarized in Table 7 and give a fairly clear indication that most favourable responses in these tests have resulted from placing both seed and fertilizer at the three inch depth. The detrimental effect of seeding at 4.5 inches depth may apparently be partly overcome by fertilization as indicated by the yield results in Table 7.

A consideration of the effect of using a fertilizer in powdered versus the granulated form shows little consistent difference (Table 8). The mean results of both harvests and at all locations indicate a significantly greater uptake of the granular as compared to the powdered material.

Radiation Effects on Plant Growth

The tacit assumption has been made that radioactive phosphorus can be used as a tracer to indicate how non-radioactive phosphorus reacts. If the radiations from P^{32} have an appreciable effect on plant physiological functions, radioactive phosphorus will not indicate correctly the reactions of inactive phosphorus.

In a greenhouse experiment, Thatcher wheat was grown in pots in Melfort silty clay soil. Ammonium phosphate was applied both in solution and in granular form at seed level. P^{32} was applied at various rates: 0, 12, 120 and 1200 microcuries P^{32} per gram P^{31}. There was no significant dfference at the .05 level between the various levels of activity for plant weight, total phosphorus, soil and fertilizer phosphorus and length of leaf for various harvest dates. A rate of 3600 microcuries P^{32} per gram P^{31}, used with

TABLE 7.—FERTILIZER PLACEMENT AT MATURITY—MEAN OF THREE LOCATIONS

Depth of seed and fertilizer	Grain yield bu./acre	Plant wt. lb./acre in hundreds	Phosphate taken up by plants				
			Total P_2O_5 lb./acre	Soil P_2O_5 lb./acre	Fert. P_2O_5 lb./acre	% recovery of applied P_2O_5	Fert. P_2O_5 as % of total P_2O_5
Seed 3″	22.9	45.0	15.5	15.5	0		0
Seed 3″ Fert. 3″	30.9	59.8	18.2	12.4	5.7	23.9	31.6
Seed 3″ Fert. 4.5″	27.7	55.4	17.6	12.6	5.0	21.0	28.7
Seed 3″ Trench 4.5″	22.6	45.3	15.9	15.9	0		0
Seed 4.5″	19.2	39.2	13.4	13.4	0		0
Seed 4.5″ Fert. 4.5″	28.8	53.0	17.8	13.1	4.7	19.5	26.4
L.S.D. (0.05)	3.5	4.5	2.2	2.0	0.5		

TABLE 8.—COMPARISON OF GRANULAR AND POWDERED PHOSPHATE

Location	Harvest	Treatment	Grain yield	Plant wt. lb./acre in hundreds	Phosphate taken up by plants: Total P_2O_5 lb./acre	Soil P_2O_5 lb./acre	Fert. P_2O_5 lb./acre	% recovery of Fert. P_2O_5	Fert. P_2O_5 as % of total P_2O_5
Birsay	Heading	Powder		3.78	1.79	0.79	1.00	4.16	55.7
		Granular		2.40	1.24	0.45	0.79	3.30	63.8
		L.S.D. (0.05)		1.36	N.S.	N.S.	N.S.		
	Maturity	Powder	3.03	4.09	1.48	0.42	1.06	4.40	71.8
		Granular	2.98	4.64	1.76	0.38	1.38	5.89	78.2
		L.S.D. (0.05)	N.S.	N.S.	N.S.	N.S.	N.S.		
Kyle	Heading	Powder		25.1	12.2	8.1	4.1	17.1	33.5
		Granular		28.4	13.8	9.3	4.5	18.9	32.6
		L.S.D. (0.05)		N.S.	1.1	N.S.	N.S.		
	Maturity	Powder	39.7	51.6	27.0	20.5	6.5	27.1	24.0
		Granular	43.4	63.1	26.3	18.8	7.5	31.0	28.6
		L.S.D. (0.05)	N.S.	N.S.	N.S.	N.S.	N.S.		
Melfort	Heading	Powder		28.6	12.1	7.1	5.0	21.1	41.7
		Granular		32.1	12.5	6.3	6.2	26.1	49.6
		L.S.D. (0.05)		2.9	N.S.	N.S	0.7		
	Maturity	Powder	50.7	64.9	29.5	21.2	8.3	34.9	28.3
		Granular	46.6	60.4	26.2	17.9	8.3	34.9	31.7
		L.S.D. (0.05)	N.S.	N.S.	N.S.	N.S.	N.S.		
Mean of three tests at maturity		Powder	31.2	60.4	19.3	14.0	5.3	22.1	27.5
		Granular	30.9	59.8	18.2	12.4	5.7	23.9	31.6
		L.S.D. (0.05)	N.S.	N.S.	N.S.	N.S.	N.S.		
Mean of two harvests at three locations		Powder			14.0	9.7	4.4		
		Granular			13.7	8.9	4.8		
		L.S.D. (0.05)			N.S.	N.S.	0.3		

TABLE 9.—RATE OF APPLICATION OF PHOSPHATE

Pounds P_2O_5 per acre	Grain yield bu./acre	Plant wt. lb./acre in hundreds	Phosphate taken up				
			Total P_2O_5 lb./acre	Soil P_2O_5 lb./acre	Fert. P_2O_5 lb./acre	% Fert. P_2O_5 used	Fert. P_2O_5 as % of total P_2O_5
	Melfort—1950						
0	43.1	55.0	25.2	25.2	0	0	0
6	45.5	60.3	25.9	23.6	2.3	39.2	8.9
12	48.2	63.4	27.8	23.6	4.2	34.8	15.0
24	50.0	67.8	29.0	21.0	8.0	33.4	27.6
48	54.0	70.7	29.2	16.1	13.1	27.3	42.5
96	57.5	74.4	32.2	11.7	20.5	21.3	63.5
L.S.D. (0.05)	6.7	8.6	4.1	3.8	1.7	4.6	
	Watson—1950						
0	24.8	41.9	15.9	15.9	0	0	0
6	26.9	47.6	17.7	15.6	2.0	35.7	12.2
12	26.6	51.8	16.9	13.7	3.2	26.4	18.4
24	30.9	58.6	20.4	13.7	6.6	27.5	32.5
48	34.6	63.0	20.4	10.4	10.0	21.1	49.8
96	35.4	61.2	21.2	7.0	14.3	14.8	67.9
L.S.D. (0.05)	5.6	7.5	2.6	2.2	1.9	5.6	
	Mean of Both Locations						
0	33.8	48.4	20.6	20.6	0	0	0
6	36.2	53.7	21.9	19.6	2.2	37.4	10.7
12	37.3	57.5	22.3	18.6	3.7	30.6	16.7
24	40.8	63.1	24.7	17.4	7.3	30.4	30.0
48	44.3	66.8	24.8	13.2	11.6	24.2	46.2
96	46.6	67.7	26.7	9.4	17.3	18.0	65.7
L.S.D. (0.05)	4.1	5.6	2.3	2.1	1.1		

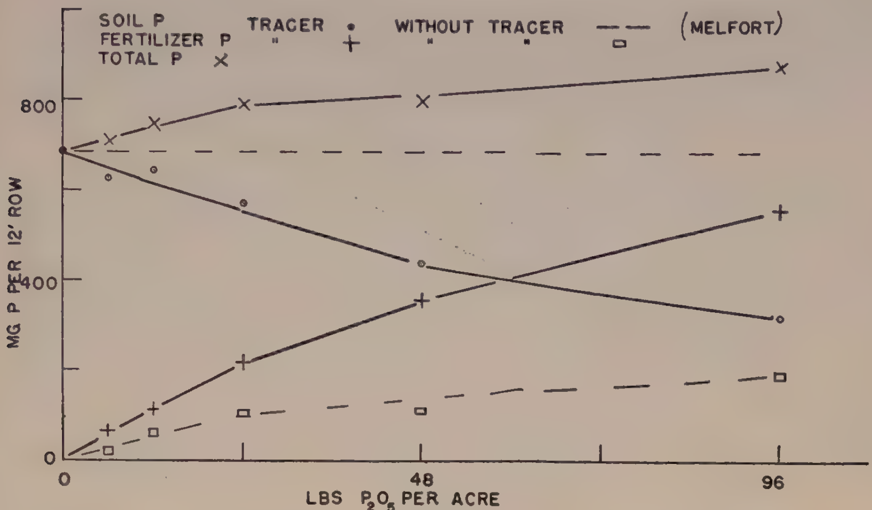

FIGURE 3. Relationship of uptake of phosphorus from soil and fertilizer with increasing rates at Melfort, Saskatchewan, 1950. Broken lines indicate results as might be calculated without the information provided through the use of tracer phosphorus.

solid fertilizer, also showed no significant radiation effect.* These results are in disagreement with those of Scott-Russell (15) but in agreement with American workers (9), and a recent publication by Thomas (1). Certainly, it would appear that the level of activity used in these experiments (100 microcuries P^{32} per gram P^{31}) has no significant effect on the results.

The Effect of Rate of Application on Fertilizer Uptake

The effect of the rate of application of 11–48–0 on the uptake of fertilizer phosphorus and soil phosphorus was investigated for Thatcher wheat. The rates employed in pounds P_2O_5 per acre were: 6, 12, 24, 48 and 96. Experimental plots were at Melfort and at Watson. The results are shown in Table 9 and Figures 2 and 3.

*E. Penner. The effect of irradiation from P^{32} in fertilizer experiments. Soils 19 thesis. University of Saskatchewan, 1951.

TABLE 10.—RATIO P FROM FERTILIZER : P from soil

Pounds P_2O_5 per acre	Melfort 1950		Watson 1950	
	P from Fert. / P from Soil	K	P from Fert. / P from Soil	K
0	0	—	0	—
6	0.098	59	0.139	43
12	0.177	68	0.256	47
24	0.382	63	0.482	50
48	0.740	65	0.992	48
96	1.74	55	2.11	45
		Av. 62		Av. 46

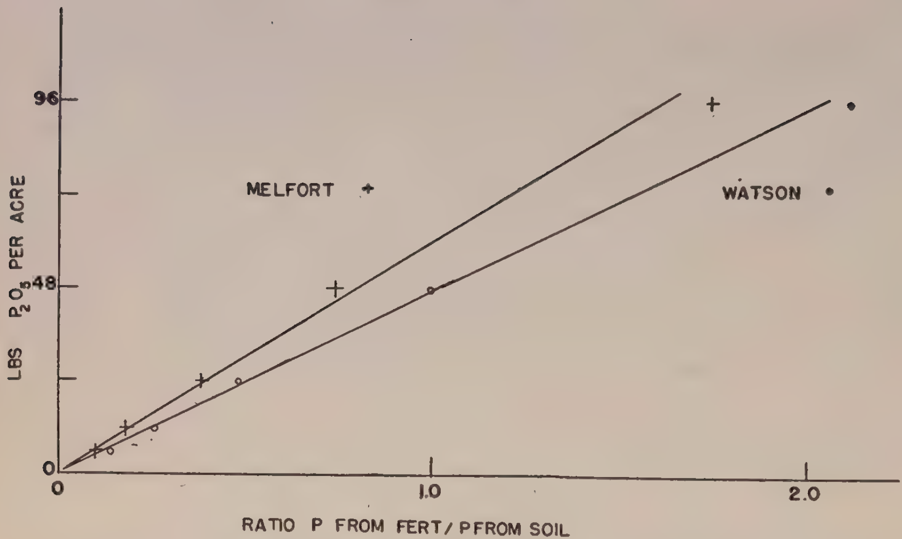

FIGURE 4. Ratio of fertilizer phosphorus to soil phosphorus in plant as related to rate of application of phosphate fertilizer. Melfort and Watson. 1950.

In general it is seen that with increasing rates of application of 11–48–0 the total P, grain yield and plant weight steadily increase while the soil P uptake steadily decreases. The fertilizer P uptake steadily increases although the per cent utilization steadily decreases.

Before the advent of tracers, fertilizer uptake was estimated by comparing the P uptake from a fertilized plot with that from a control plot, the assumption being made that an equal quantity of soil phosphorus is taken up from fertilized and control plots. The values obtained in this way are shown by the broken line in Figure 3. They can obviously be greatly in error.

Available Soil Phosphorus

In Figure 4, the rate of application of fertilizer has been plotted against the ratio of P from fertilizer/P from soil (*see also Table 10*). For Melfort soil, it appears that when 11–48–0 is applied at 60 pounds P_2O_5 per acre, soil and fertilizer contribute equal amounts of phosphorus to the plant, or in other words, the soil P used is equivalent to that supplied by 60 pounds P_2O_5, as 11–48–0, per acre.

It is also of considerable interest that the points lie on a reasonably straight line. The slope of this line, K, gives a measure of available soil P in terms of 11–48–0. The slopes for soils at Melfort and Watson differ appreciably. This behaviour has been found by a number of workers and seems to be quite general (7). Having established that this behaviour is quite general the slope of the line can be determined by doing experiments for just one or two rates of application. In fact K = (rate of application of fertilizer) $\times \frac{(\%\ \text{P from soil})}{(\%\ \text{P from fert.})}$. The theoretical basis for this expression has been discussed by Larsen (12) and by Fried and Dean (7).

Having determined K, fertilizer utilization can be calculated for other rates of application of fertilizer (always, of course, for the same soil, crop, season, and mode of application of fertilizer). Further related work is underway in connection with this phase of the experiments.

SUMMARY

P^{32} labelled fertilizers have been used to determine the availability of phosphorus fertilizers of analysis 0–20–0 and 11–48–0 to Exeter oats, Titan barley, Montcalm barley and Thatcher wheat. The effect of varying the rate of application of 11–48–0 from 0 to 96 pounds P_2O_5 per acre on the uptake of fertilizer by wheat plants was investigated for soils at Melfort and Watson. Extensive placement experiments were done at Birsay, Kyle and Melfort. For the soils, crops, and fertilizers tried, 11–48–0, ammonium hydrogen phosphate, gave the largest uptake of fertilizer. The uptake was at a maximum when granulated fertilizer was placed at 3 inches and the seed at 3 inches. Experiments on radiation effects are also reported.

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SOIL FERTILITY STUDIES

III. MANURE AND FERTILIZERS FOR FIELD CROPS AT KAPUSKASING, ONTARIO[1]

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An investigation to determine the effect of manure and commercial fertilizers on the growth of grain and hay crops on the clay areas of Northern Ontario was begun in 1926 at the Dominion Experimental Station at Kapuskasing. This station was established in 1916. The location at latitude 49° 25′ has a rather severe climate. The records for the 32-year period 1918-1949 showed that the average frost-free period was 82.8 days, the average monthly precipitation for May to September inclusive being 2.88 inches and the average temperature for these months 55.6° F.

The soil at the Kapuskasing Station is derived from a high lime, varved clay material. On the surface, there are frequent depressions filled with muck and in laying out the experiment it was necessary to omit small areas in order to avoid having individual plots on muck. Even with this procedure, the organic matter content of the soil from the different plots showed considerable variation. The analyses of 12 samples of surface soil taken from different plots at the beginning of the experiment showed that the loss on ignition varied from 4.19 to 14.03 (average 7.93) per cent and the nitrogen content from 0.12 to 0.36 (average 0.21) per cent. The mean pH value was 6.4.

OUTLINE OF EXPERIMENT

The site selected for the experiment had been under cultivation for only a short time. The area was divided into four blocks, providing for the growing of each crop of a four-year rotation each year. Each block consisted of 24 plots, 16 feet by 68 feet, equivalent to one-fortieth acre. Part A of Figure 1 shows the nine treatments used with three check plots interspersed. These 12 plots were duplicated in each block in the order shown and not randomized. Thus each block consisted of nine treatments in duplicate, and six check plots. The rotation was oats, peas and vetch (O.P.V.) the first year, followed in turn by barley, clover hay and timothy hay. The fertilizers were applied to the O.P.V. crop.

In 1936, the experiment was revised to permit a study of the effect of increased rates of fertilizer and manure. Each of the original plots of one-fortieth acre was split into two plots, 16 feet by 27.2 feet, equivalent to one-hundredth acre. Part B of Figure 1 shows the complete new set of treatments and check plots which was duplicated in each block. Of the original treatments, the calcareous subsoil was omitted in the revision and sulphur at the rate of 100 lb. per acre was substituted on one half, the other half of the original plot (No. 11) receiving no further treatment. The fertilizers were applied to the O.P.V. crop except where otherwise stated in the "Revised Plan" (Figure 1).

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A. Original Plan—1926. (One replicate. Second replicate plots numbered 13 to 24)

1.	Manure—8 tons
2.	Check
3.	Nitrate of soda ($NaNO_3$)—100 lb. Superphosphate —250 lb. Muriate of potash (KCl)— 50 lb.
4.	Nitrate of soda ($NaNO_3$)—100 lb. Superphosphate —250 lb.
5.	Superphosphate —250 lb. Muriate of potash (KCl)— 50 lb.
6.	Check
7.	Nitrate of soda ($NaNO_3$)—100 lb. Muriate of potash (KCl)— 50 lb.
8.	Nitrate of soda ($NaNO_3$)—100 lb
9.	Superphosphate —250 lb.
10.	Check
11.	Calcareous subsoil — 4 tons
12.	Basic slag —500 lb.

B. Revised Plan—1936. (One replicate. Second replicate plots numbered 25 to 48)

1.	Manure — 8 tons	13.	Manure— 16 tons Super. —250 lb.
2.	Check	14.	Manure— 16 tons Super. —500 lb.
3.	$NaNO_3$ —100 lb. Super. —250 lb. KCl — 50 lb.	15.	$NaNO_3$—200 lb. Super. —500 lb. KCl —100 lb.
4.	$NaNO_3$ —100 lb. Super. —250 lb.	16.	$NaNO_3$—100 lb. Super. —500 lb. KCl — 50 lb.
5.	Super. —250 lb. KCl — 50 lb.	17.	$NaNO_3$ — 50 lb. Super. —125 lb. } Applied annually KCl — 25 lb.
6.	Manure — 16 tons	18.	Check
7.	$NaNO_3$ —100 lb. KCl — 50 lb.	19.	Manure— 8 tons $NaNO_3$—100 lb. Super. —250 lb. KCl — 50 lb.
8.	$NaNO_3$ —100 lb.	20.	$NaNO_3$—100 lb. } +$NaNO_3$—50 lb., Super. —500 lb. } for barley and KCl —100 lb. } timothy
9.	Super. —250 lb.	21.	Super. —500 lb.
10.	Check	22.	Super. —250 lb. for O.P.V. Super. —100 lb. for barley Super. —150 lb. for clover
11.	Sulphur —100 lb.	23.	Check
12.	Basic slag—500 lb.	24.	Super.—1000 lb. for 1st rotation and Super.—250 lb. for each subsequent rotation

FIGURE 1. Plan of experiment

TABLE 1.—AVERAGE YIELDS PER ACRE

Treat-ment* No.	Treatments per acre (applied for O.P.V. crop)	O.P.V. (D.M.)			Barley** (Grain)			Clover** (D.M.)			Timothy*** (D.M.)		
		1926-1935	1936-1946	1926-1946	1927-1936	1937-1946	1927-1946	1928-1937	1938-1946	1928-1946	1929-1938	1939-1946	1929-1946
		lb.	lb.	lb.	bu.	bu.	bu.	lb.	lb.	lb.	lb.	lb.	lb
1	Check	3080	2173	2605	22.4	20.3	21.5	1261	1419	1331	990	1580	1248
2	N ($NaNO_3$—100 lb.)	3397	2428	2890	22.0	20.0	21.1	1214	1406	1 99	9·8	1536	1222
3	P (Super.—250 lb.)	3687	2849	3248	23.4	24.8	24.1	1852	2579	2175	1339	2392	1800
4	NK {$NaNO_3$—100 lb. KCl—50 lb.}	3314	2567	2923	21.9	22.4	22.1	1154	1480	1299	965	1621	1252
5	NP {$NaNO_3$—100 lb. Super.—250 lb.}	4269	2989	3599	25.6	26.9	26.2	1878	2738	2260	1427	2285	1803
6	PK {Super.—250 lb. KCl—50 lb.}	3967	2867	3391	25.4	26.7	26.0	1896	2738	2271	1403	240	1839
7	NPK {$NaNO_3$—100 lb. Super.—250 lb. KCl—50 lb.}	4249	2973	3580	26.4	28.8	27.5	1811	2778	2241	1539	2497	1958
8	Manure—8 T.	3713	2996	3338	25.3	30.4	27.5	1697	3235	2381	1351	3062	2100
9	Basic Slag—500 lb.	3851	2764	3281	23.2	29.6	26.0	2194	3174	2630	1444	2982	2117
10	Manure—16 T. + Super.—250 lb. (1926-35, Manure 8 T.)	—	3460	—	—	32.7	—	—	4066	—	—	4075	—
11	Manure—16 T. + Super.—500 lb. (1926-35, Check)	—	3515	—	—	32.4	—	—	4303	—	—	3880	—
12	Manure—16 T. (1926-35, Check)	—	3378	—	—	32.1	—	—	3750	—	—	3137	—
13	Super.—500 lb. (1926-35, Super.—250 lb.)	—	2984	—	—	25.6	—	—	3278	—	—	2909	—
14	NPK ($NaNO_3$—200 lb., Super.—500 lb.) (KCl—100 lb.) (1926-35, NPK at half this rate)	—	3800	—	—	29.9	—	—	3455	—	—	3156	—

* Treatment number bears no relation to plot number.
** No yields of barley or clover in 1943 or barley in 1946.
*** No yields of timothy in 1938 or 1944.

In 1947, the experiment was discontinued temporarily, the area being fallowed in order to destroy a severe infestation of sow-thistle. It appeared to be an opportune time to examine the results obtained in order to determine the effects of the treatments on crop yield and soil composition.

YIELD RESULTS

A complete set of yield data was available for the O.P.V. crop. There were no yields of barley in 1943 and 1946, of clover in 1943 or of timothy in 1938 and 1944. In the case of barley, excessive rain in 1943 had a detrimental effect on the crop which was on the average less than 12 inches in height and was considered a complete failure; in 1946, late seeding, a prolonged summer dry spell and early fall frosts combined to give a crop failure. No clover yields were taken in 1943; due to the spread of sow-thistle in the plots, steps had to be taken to control it and the block was ploughed in June and kept fallow for the rest of that year and all of 1944. This resulted also in no timothy yields in 1944. Since the treatments were not randomized and since the experiment lacked orthogonality in respect to the design, no attempt has been made to evaluate the results by the use of statistical methods. However, the results from duplicated treatments carried on for a number of years revealed substantial differences in yield according to the treatments.

The mean annual yields from nine of the original treatments and from five of the treatments begun at the time of revision of the project are presented in Table 1. With regard to the nine original treatments, in addition to the mean annual yields for the entire period of the experiment, the mean values are given for the two periods: (*a*) up to the time of revision and (*b*) following revision. The latter values can be compared with those for the five new treatments over the same period.

The yields of all crops in the rotation were substantially increased as a result of the phosphorus component of the fertilizer (Table 2). The O.P.V. was the only crop to show any appreciable increase in yield from applied nitrogen, and potassium had but slight effect on the yield of any of the crops.

Manure at 8 tons per acre (Treatment 8, Table 1) and the complete fertilizer (Treatment 7) gave somewhat similar results based on the whole experimental period, but it is interesting to note that during the first period of the experiment the complete fertilizer was superior to manure, whereas during the latter period, manure was superior, particularly in respect to the residual effect on the hay crops. Basic slag applied at 500 pounds per acre (Treatment 9) and the superphosphate treatment at 250 pounds per acre (Treatment 3) gave similar yields of O.P.V., but the residual effect of basic slag on the yield of barley and hay crops was greater than that obtained from the superphosphate.

In respect to the new treatments following revision of the experiment in 1936, increasing the rate of superphosphate from 250 (Treatment 3) to 500 pounds per acre (Treatment 13) brought about an increase in the yield of all crops but especially clover and timothy. Similarly, the double rate of complete fertilizer (Treatment 14) increased the yield of all crops over that obtained with the lower rate (Treatment 7). Manure at 16 tons

TABLE 2.—EFFECT OF FERTILIZER CONSTITUENTS ON YIELDS

	O.P.V., 1926-1946	Barley, 1927-1946	Clover, 1928-1946	Timothy, 1929-1946
	lb./ac.	bu./ac.	lb./ac.	lb./ac.
Effect of nitrogen—				
N—Check	285	−0.4	−32	−26
NP—P	351	2.1	85	3
NPK—PK	189	1.5	−30	119
Average	275	1.1	8	32
Effect of phosphorus—				
P—Check	643	2.6	844	552
NP—N	709	5.1	961	581
NPK—NK	657	5.4	942	706
Average	670	4.4	916	613
Effect of potassium—				
NK—N	33	1.0	0	30
PK—P	143	1.9	96	39
NPK—NP	−19	1.3	−19	155
Average	52	1.4	26	75

per acre (Treatment 12), though applied to previously untreated plots gave larger yields than manure at 8 tons on previously manured plots (Treatment 8). When both manure at 16 tons and superphosphate at 500 pounds per acre were applied together to a former check plot (Treatment 11) the yields of clover and timothy were increased appreciably over those obtained with 16 tons of manure only (Treatment 12). Treatments 10 and 11, both of which consisted of manure supplemented with superphosphate, were the two best treatments employed, considering the overall production of the whole rotation.

A comparison of the results for the two periods for which yield data are presented showed that the mean annual yields of the O.P.V. crop for the years before the revision of the experiment were greater than for the period following revision, but the reverse was true for the other crops. Although no yield data are presented for the individual years, the results varied from year to year according to seasonal conditions.

EXAMINATION OF SOIL SAMPLES

In the fall of 1948, after the area had been fallowed for two seasons, surface soil samples (0″-6″) were collected from certain of the plots in Block 3. This block was selected for sampling because samples taken at the time the experiment was begun were available for comparison. Samples were also collected from a few of the plots in Block 1 in which the soil appeared to be more uniform than in Block 3. The results of analysis of the Block 3 samples are given in Table 3, with the figures for the 1928 and

TABLE 3.—ANALYSES OF SOIL SAMPLES FROM BLOCK 3

(Collected in 1928 and in 1948)

Treatment	Plot No.	pH		% Loss on ignition		% Nitrogen		Exchangeable bases					
								% CaO		% MgO		% K_2O	
		1928	1948	1928	1948	1928	1948	1928	1948	1928	1948	1928	1948
Check	2	—	6.9	5.36	4.75	0.16	0.13	0.775	0.750	0.093	0.097	0.024	0.022
	10	6.4	7.5	5.13	4.34	0.15	0.13	0.523	0.889	0.064	0.111	0.013	0.022
	18	6.1	6.6	5.85	4.88	0.17	0.14	0.545	0.621	0.058	0.094	0.012	0.016
	26	6.3	6.5	14.03	8.00	0.35	0.23	1.318	0.903	0.125	0.125	0.020	0.017
	34	6.5	6.7	6.97	5.66	0.17	0.15	0.677	0.668	0.083	0.096	0.015	0.015
	42	6.4	6.9	7.96	5.84	0.21	0.16	0.724	0.683	0.089	0.093	0.015	0.018
NK	7	—	6.9	—	4.21	—	0.14	—	0.760	—	0.100	—	0.017
	31	—	7.2	—	7.08	—	0.20	—	0.843	—	0.120	—	0.017
Manure— 8 T.	1	—	7.0	—	4.27	—	0.13	—	0.684	—	0.085	—	0.019
	25	—	6.8	—	13.40	—	0.23	—	0.916	—	0.129	—	0.018
Manure—16 T.	6	6.2	7.1	5.57	4.31	0.16	0.13	0.666	0.795	0.089	0.101	0.016	0.017
	30	6.4	7.1	11.06	7.13	0.29	0.20	0.977	0.880	0.108	0.113	0.019	0.020
Superphosphate—500 lb.	21	—	6.8	—	8.43	—	0.26	—	0.864	—	0.120	—	0.012
	45	—	6.8	—	5.80	—	0.15	—	0.709	—	0.107	—	0.016
Manure—16 T. Superphosphate—500 lb.	14	6.4	6.5	4.19	4.54	0.12	0.13	0.622	0.642	0.068	0.091	0.019	0.017
	38	6.1	6.6	13.79	7.65	0.36	0.22	1.051	0.802	0.110	0.105	0.017	0.016

TABLE 4.—READILY SOLUBLE PHOSPHORUS IN SOIL SAMPLES

(Expressed as p.p.m. P in air-dry soil)

Treatment	Plot No.	Extracted with NH_4HSO_4 (pH 3.0) (Truog method)			Extracted with $KHSO_4$ (pH 2.0) (Ruhnke method)			Extracted with K_2CO_3 (1% solution) (Colorado method)		
		Block 3, 1928	Block 3, 1948	Block 1, 1948	Block 3, 1928	Block 3, 1948	Block 1, 1948	Block 3, 1928	Block 3, 1948	Block 1, 1948
Check	2	—	103	123	—	153	182	—	37	40
	10	143	45	87	180	183	154	45	27	41
	18	99	118	88	121	162	162	53	44	46
	26	15	43	98	48	140	150	66	41	47
	34	120	126	19	193	183	129	47	38	42
	42	90	99	106	133	151	148	52	41	38
NK	7	—	98	—	—	173	—	—	40	—
	31	—	45	—	—	144	—	—	47	—
Manure—8 T.	1	—	110	—	—	164	—	—	39	—
	25	—	56	—	—	164	—	—	50	—
Manure—16 T.	6	107	72	104	130	158	172	47	33	58
	30	34	44	98	104	160	137	69	62	59
Superphosphate—500 lb.	21	—	46	81	—	120	154	—	59	82
	45	—	118	68	—	183	143	—	51	66
Manure—16 T. Superphosphate—500 lb.	14	127	100	130	146	148	192	39	44	83
	38	34	82	104	85	154	150	70	79	77

1948 samples shown in adjacent columns. The plot numbers are those used after the revision in 1936. The samples collected in 1928 represented the original large plots whereas those collected in 1948 represented the smaller plots which resulted from the revision.

Although the pH values of the original samples showed little variation in reaction from plot to plot, the results for organic matter as measured by loss on ignition and nitrogen content, and for exchangeable bases, varied over a wide range. In every case, the pH value of the soil increased from 1928 to 1948. This change may have been due in part to the incorporation of varying amounts of the calcareous subsoil during the cultivation of the plots over the years. In all but one case (Plot 14) the organic matter content decreased, the decreases being greatest on the plots which had the largest amount of organic matter originally.

Changes in the exchangeable base content showed no definite trend as both increases and decreases took place. Frequently a close relationship can be observed between pH values and exchangeable calcium and magnesium in soils of similar base exchange capacity. However, changes in organic matter content result in changes in base exchange capacity and this interferes with the above relationship. In the samples under investigation, the greatest decreases in exchangeable calcium were found on the plots where there was the greatest decrease in organic matter content (Plots 26, 30, 38). On the other hand, the greatest increases in exchangeable calcium occurred on Plots 6 and 10 where the original organic matter content was comparatively low and where the greatest increases in pH values were found.

It was impossible to show any effect of treatment on soil composition. The variation among the six check plots and the variation between duplicate plots receiving the same treatment was so great that any treatment effect was completely obscured. In the case of Block 1, for which no data are presented, the range of values was much less but the variation among check plots and between duplicates was such that again no effect of treatment on soil composition could be determined.

In view of the beneficial effect of phosphorus on crop yields, it was of interest to obtain information on the phosphorus availability in the soil as measured by chemical methods. It has been the experience in this laboratory that no method of measuring the so-called "available" phosphorus is applicable in all cases and a method that may give results which correlate with response to phosphatic fertilizers or which reflect soil treatment under one set of soil conditions may give erratic results with another. For this investigation, three chemical methods were employed: (1) The Truog method in which the extracting solution is ammonium sulphate adjusted to pH 3.0; (2) the Ruhnke method in which the extracting solution is potassium bisulphate at pH 2.0; and (3) the Colorado method in which the extracting solution is a 1 per cent solution of K_2CO_3 at pH 12.0.

Results obtained on the two sets of samples from Block 3 and on the set from Block 1 are presented in Table 4. With both the Truog and the Ruhnke methods, the range of results was very wide and the variation among the untreated plots and between duplicates of treated plots was such that no effect of soil treatment could be observed. With the Colorado

method, the range of values obtained was much narrower and there was some indication that the results might be related to the treatments. In the case of Block 3, a decrease in readily soluble phosphorus from 1928 to 1948 was shown for all untreated plots and also for those receiving 16 tons of manure after the revision in 1936; a small increase was found where the treatment was manure at 16 tons and superphosphate at 500 lb. With the Block 1 samples, results for phosphorus soluble in 1 per cent K_2CO_3 agreed very well with the soil treatments.

SUMMARY

The effect of applications of manure and commercial fertilizers was studied at the Dominion Experimental Station, Kapuskasing, Ontario, over the period 1926 to 1948. The materials were applied to an oats, peas, vetch (O.P.V.) crop in a 4-year rotation of O.P.V., barley, clover and timothy up to 1936. At that time, the plan of the experiment was revised to include heavier rates of treatment and, in some cases, application of the materials at different times in the rotation.

Nitrogen brought about some increase in the O.P.V. yields but otherwise, nitrogen and potash had little effect on the crop yields.

Superphosphate at 250 lb. per acre and manure at 8 tons per acre each gave substantial increases in the yield of all crops in the rotation. Further yield increases were obtained by increasing the superphosphate rate to 500 lb. and the manure rate to 16 tons per acre. The best yields were obtained from a combination of manure and superphosphate.

Over the period of the experiment, the pH values of the surface soil increased and the organic matter content decreased. Soil variation from plot to plot was so great that no effect of treatment on soil composition could be shown.

THE NATURE OF THE CLAY MINERALS IN SOME SASKATCHEWAN SOILS[1]

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Little information (5, 12) is available on the nature of the clay fraction of Saskatchewan soils. Because of the importance of this fraction in determining chemical and physical properties of soils, and as a possible aid in classification, this investigation was undertaken. Soils were chosen representing, as far as possible, the entire range of climatic and vegetational differences, from the semi-arid Brown soils of the grassland region to the podzolized soils of the forest region. The soils studied gave a wide range of physical and chemical properties, and were chosen as being most likely to demonstrate the mineralogical differences that might exist.

Montmorillonite, illite (or hydrous mica) and kaolinite are usually considered to be the most generally occurring clay minerals. Montmorillonite $(OH)_4Al_4Si_8O_{20}$ (7) is a 2 : 1 lattice mineral expanding along the c axis with hydration, having a base exchange capacity up to 120 me./100 gm. and having high plasticity and cohesion. Illite $(OH)_4K_y(Al_4 . Fe_4 . Mg_4 . Mg_{.6})$ $(Si_{8-y} . Al_y)O_{20}$ (7) is a 2 : 1 lattice mineral with a base exchange of about 40 me./100 gm. and a fairly high content of fixed potassium. It does not expand with hydration and has only moderate plasticity and cohesion. Kaolinite $(OH)_8Al_4Si_4O_{10}$ (7) is a 1 : 1 lattice mineral, non-expanding, with a low base exchange capacity (1-15 me./100 gm.) and low plasticity and cohesion. These, or varieties of these mineral groups, are of greatest occurrence in soils, and on the basis of either physical properties or parent materials, the presence of all three groups might be suggested in Saskatchewan soils.

METHODS

Three general basic methods of analysis were used: (1) chemical; (2) differential thermal; and (3) X-ray diffraction.

Chemical

Chemical analysis is an essential method of investigation and yields results of great value when used in combination with physical methods. Due to isomorphous substitution molecular ratios such as $SiO_2 : R_2O_3$ are not reliable criteria for identification of the clay minerals. However, similarity of analysis does indicate a similar clay mineral content. Further, if the amount of iron combined with silica exceeds 2 per cent Fe_2O_3, 2 : 1 layer lattice minerals are present. The same is indicated if the amount of MgO exceeds 1 per cent (11). If these are not present it does not prove that 2 : 1 layer lattice minerals are absent. The determination of non-exchangeable potassium gives information on the presence of illite as potassium is an essential constituent of this mineral and not of montmorillonite or kaolinite. A semi-quantitative estimation may be obtained of

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the amount of illite present if 6 per cent K_2O is taken as representing 100 per cent illite. Due to the variable potassium content of illite this cannot be relied on too greatly.

The methods used in the silicate analysis are well established methods. Briefly, the methods used are as follows:

The sample was fused with Na_2CO_3 and the fusion cake dissolved in water and HCl.

Silica was determined after a double dehydration, by loss in weight when treated with HF.

The sesquioxides were determined by weight after being precipitated with NH_4OH.

Iron was determined on the sesquioxides by fusion with $K_2S_2O_7$, the fusion dissolved in weak H_2SO_4 and the resulting solution passed through a Jones reductor and titrated with standard $KMnO_4$.

Titanium was determined colorimetrically after oxidation with H_2O_2.

Aluminum was determined by difference from total sesquioxides and Fe_2O_3 and TiO_2.

Calcium was not determined as no precipitate could be observed on addition of $(NH_4)_2C_2O_4$.

Magnesium was determined by precipitation from a strongly ammoniacal solution with $NaNH_4HPO_4$, drying the precipitate at a low temperature, dissolving the precipitate in standard acid and back titrating the excess acid with standard NaOH.

The total base exchange capacity was determined by the method of Bower and Truog (4) using the colorimetric manganese method.

Non-exchangeable potassium was determined by the method of Bailey (1), the method being based on the precipitation of potassium as $K_2NaCo(NO_2)_6$ in dilute HNO_3, and on the subsequent colorimetric determination of the cobalt in the precipitate as cobalt hydrocarbonate.

X-ray Powder Diffraction

When a powdered crystalline substance is examined in an X-ray diffraction apparatus a series of lines may be recorded on a photographic film. These lines are related to the interplanar spacings of the crystals. The diffraction pattern is characteristic of the substance which produced it. From X-ray diffraction patterns of soil clays a number of reflections are obtained which are characterized by their position, width and relative intensities and which can be expressed as lattice spacings in A°. The range of the spacings in soil clays vary from 1A° to over 20A°. In identification of the clay minerals it is more reliable to use the wide spacings only, characteristic of c axis spacings.

The X-ray diffraction patterns were obtained with a General Electric X.R.D. unit operated at 30 Kv., A setting at 25 m.a. for one hour using Cu α radiation. The camera radius was 14.324 cm. and the slit on the camera was a pinhole having a defining diameter of 0.030 inches and a maximum beam divergence of 1.68°.

The sample was prepared for X-ray powder diffraction analysis by saturating the clay with calcium, drying, grinding to pass a 100-mesh sieve, then adding glycerol until the clay was just moist. The samples were then

allowed to stand for a month so that the clay and the glycerol were in equilibrium. The clay sample was then formed into a triangular prism in the recess of the sector mount. The edge of the prism wedge was elevated into the X-ray beam so that it cut two-thirds to three-quarters of the beam.

Differential Thermal Analysis

The differential thermal analysis method is based on the fact that the application of heat to many minerals causes certain physical and chemical changes which are reflected in endothermic and exothermic reactions. The temperature of the test material is measured relative to that of an inert material which is being heated in the same manner. By comparing the difference in temperature between the test sample and the inert material a curve is obtained which is characteristic for that test material.

A positive deflection indicates a liberation of energy because of an exothermic reaction. A negative deflection indicates some reaction which absorbs energy. Molecular rearrangement would be expected to be exothermic since the system would presumably shift to a more stable arrangement and thus release energy. To drive off water would require energy thus giving an endothermic effect. The identification of the mineral types is based mainly on observations of the temperature of the peak or peaks of the differential thermal curve.

All of the clay minerals show an endothermic reaction between 20° and 200° C. representing the loss of adsorbed water. This curve is not a reliable guide in identification as it is affected by the particle size, the relative humidity at which the sample was dried, the nature and amounts of the exchangeable cations and the state of aggregation of the particles (2).

The kaolinite minerals have two well defined thermal reactions—a very large endothermic reaction between 550° and 600° C., and a very sudden and pronounced exothermic reaction between 950° and 1000° C. The endothermic reaction is due to the complete loss of water from the crystal lattice, after which the sample is amorphous until the exothermic reaction, which is due to the recrystallization of amorphous Al_2O_3 (11). This exothermic reaction is characteristic of the kaolin group of minerals. Less than 5 per cent of kaolin in a mixture may be positively identified. In illite the reactions are not as pronounced. Endothermic reactions occur between 500° and 650° C. and at about 900° C. with a small exothermic reaction immediately following the latter.

In general, montmorillonite minerals give a curve similar to that of illite except that the endothermic reaction at 500° to 650° C. in illite is usually about 100° C. higher in montmorillonite (8). However, where there is a high replacement of aluminum by iron in montmorillonite the endothermic reaction takes place in the same temperature range as for illite (14) making it impossible to distinguish between the two when they occur together.

In the 2 : 1 layer lattice minerals the endothermic reaction between 500° and 750° C. represents the loss of most of the water of the crystal but the essential micaceous character of the mineral is maintained until about 900° C. when the last water is driven off. The exothermic reaction at about 900° C. represents a molecular rearrangement as spinel ($MgAl_2O_4$) is formed. The endothermic reaction in illite occurs at a lower temperature

than that in montmorillonite because of the extensive substitution in illete of aluminum for silicon. This is responsible for an alteration in the stability of the structure resulting in a relatively large water loss at a lower temperature (16).

The apparatus used for the differential thermal analysis was patterned after that of Grimshaw *et al.* (9) except that no temperature-measuring or control gear was used. The temperature of the reference material was taken with a Hoskins high resistance pyrometer. The differential temperature was taken with a mirror-type galvanometer.

The test sample and the reference material, Al_2O_3, were well packed into the holes of the sample holder using the flattened end of a glass rod. The samples were not weighed. The rate of heating ranged from 10° to 20° C. per minute. The heating rate was not constant but it was reproducible. It was similar to that used by Roberts (17).

Temperature readings on the inert material were taken every 3 minutes and the galvanometer deflection on the differential temperature was taken at least every 15 seconds when a thermal reaction was taking place. The temperature of the reference material was plotted on the X-axis and the galvanometer deflection on the Y-axis of squared paper, resulting in a differential thermal curve.

MATERIALS

The clay fraction of the samples used in this study was obtained from the soils described in Table 1.

These materials were selected to cover the range of climatic conditions in Saskatchewan, and to ascertain whether the different conditions of soil weathering had produced different clay minerals in the various profiles or in the various horizons within the profiles. The observation that the "greywooded" podzolic A_2 was much less sticky, on the basis of comparable clay contents, than the chestnut or chernozem soils would suggest a difference in the nature of the clay produced under these different weathering conditions. The same comment applies to the A_2 of solodized-solonetz and

TABLE 1.—DESCRIPTION OF SOILS

Association	Zone	Remarks	Horizons
Waitville	Grey	Grey wooded (podzolic)	A_1, A_2, B, B(ca), C
Melfort	Black	Chernozem	A, B_1, B(ca), G, C
Regina	Dark brown	Chestnut	A, B_1, B_2, C
Val Marie	—	Recent alluvium from cretaceous shales	A(saline), B-C, A
Sceptre	Brown	Loose top	A
Echo	Brown	Eroded, solodized-solonetz	B_1, B_2, B(ca), C
Estevan	Dark brown	Solod	C
Trossachs	Dark brown	Solodized-solonetz	A, A_2, A_3

solod profiles. In addition to climatic variations influencing weathering, differences in the source of parent materials might be expected to have an effect on clay mineral nature. The solodized-solonetz and solod profiles are commonly considered to be related to a higher shale content in the parent material, and some suspicion that a similar factor operates in the heavy clay "loose-top" profiles has also been expressed. The Val Marie soils represent sediments derived from cretaceous shales, and consequently should illustrate the influence of this parent material on clay formation, if any such differential effect operates. These soils are appreciably "heavier" than their clay contents would indicate.

Preparation of the Clay Fraction

The air-dry soil sample was ground to pass a 40-mesh sieve and the organic matter destroyed by repeated treatments with H_2O_2. The resulting sample was suspended in water and coarse material was allowed to settle out. The suspension was decanted and flocculated with NaCl. The floc was then transferred to centrifuge tubes and washed five times with 1N NaCl in order to saturate the base exchange complex with sodium. The sample was then washed with alcohol until free of chloride and excess sodium, then dispersed in water and centrifuged for the required length of time as calculated from Baver's formula (3). The suspension was flocculated with alcohol and dried at 100° C. on a water bath and was then ground in an agate mortar to pass a 100-mesh sieve, preparatory to the analysis described earlier.

The fraction studied was that with an equivalent settling diameter of < 0.001 mm. This size was chosen for convenience in time of centrifuging, and because it should be representative of the secondary minerals present, without excessive contamination by primary minerals.

It is recognized that a study of the relatively coarse clay and the fine clay separately could yield more information, but for this exploratory study the clay fraction < 0.001 mm. was investigated as a whole.

No pre-treatment for removal of free iron oxides was given since the clay suspensions were grey, yellowish-grey, or brownish-grey in colour and in no case had the reddish-brown colours associated with the presence of ferric oxides. It was considered that the error involved in not pre-treating for iron oxide removal would be less than the possible alteration effects of the treatment.

RESULTS

The data from the chemical analyses are given in Table 2.

Chemical Analysis

From this data it is seen that the analysis for all samples is very similar. There is no appreciable variation between profiles. This indicates a uniformity of at least the major constituents of the clay minerals present. The MgO content is well above 1 per cent which indicates that a high proportion of 2 : 1 layer lattice minerals are present. There is no correlation between MgO content and base exchange values. The K_2O content is also high, indicating an appreciable amount of illite. Assuming that

TABLE 2.—CHEMICAL ANALYSES OF THE < 0.001 MM. CLAY FRACTION OF SOIL SAMPLES

Profile	Horizon	Hyg. moisture	Ignition loss	SiO_2	Fe_2O_3	TiO_2	Al_2O_3	MgO	K_2O	Total Oxides	SiO_2/R_2O_3 ratio	B.E.C. m.e./100 gm.
		%	%	%	%	%	%	%	%	%		
Waitville	A_1	4.85	9.77	49.40	11.06	0.98	25.03	2.95	—	—	2.62	48.7
	A_2	4.80	10.06	49.97	11.24	0.84	22.45	2.62	2.72	99.90	2.84	45.7
	B	3.51	11.25	48.47	11.98	0.79	20.98	2.50	2.37	98.34	2.88	41.7
	B(ca)	3.69	10.23	49.24	10.24	0.82	21.08	3.24	2.51	97.36	3.03	51.2
	C	5.45	10.41	51.87	10.64	0.74	19.50	3.63	2.59	99.56	3.35	50.8
Melfort	A	5.23	10.82	52.47	9.57	0.62	20.13	2.90	2.57	99.08	3.40	—
	B_1	5.25	9.05	54.15	11.35	0.62	18.04	2.73	—	—	3.64	51.9
	B(ca)	—	—	—	—	—	—	—	—	—	—	53.5
	G	5.55	9.79	51.67	10.83	0.75	22.01	3.71	2.84	100.60	3.03	51.7
	C	5.39	8.19	52.80	9.59	0.72	23.28	2.96	2.71	100.25	3.06	51.8
Regina	A	6.81	10.98	52.82	9.13	0.79	22.73	2.65	2.93	102.03	3.14	53.0
	B_1	6.85	10.50	52.63	8.80	0.74	21.63	3.97	2.72	100.99	3.21	60.1
	B_2	7.10	10.58	50.40	9.14	0.69	21.47	3.57	2.96	98.81	3.15	59.0
	C	4.76	10.66	51.38	8.61	0.68	23.31	3.19	2.60	100.43	3.05	45.5
Val Marie	A saline	4.64	9.87	50.72	11.82	0.78	20.34	3.17	2.79	99.49	3.09	55.9
	B-C	5.90	8.83	55.15	9.87	0.77	19.89	3.44	2.61	100.56	3.58	59.5
	A	6.34	8.56	53.93	9.92	0.72	20.33	2.80	2.45	98.71	3.43	62.0
Sceptre	A	6.97	10.17	52.45	8.62	0.77	21.03	3.97	2.31	99.32	3.36	55.7
Echo	B_1	4.26	10.08	51.12	11.08	0.83	21.08	2.70	2.24	99.13	3.09	44.4
	B_2	4.35	9.05	51.94	11.01	0.81	21.69	3.04	2.43	100.06	3.07	39.7
	B(ca)	4.96	10.48	50.74	10.20	0.87	20.27	3.67	2.40	98.63	3.23	42.1
	C	4.00	8.50	53.00	10.55	0.78	21.44	2.94	2.17	99.38	3.20	51.8
Estevan	C	7.36	10.36	49.29	10.48	0.70	20.40	4.93	2.72	98.88	2.96	58.1
Trossachs	A	5.65	11.14	51.72	8.08	0.86	20.75	2.68	3.51	98.74	3.39	50.9
	A_2	5.55	12.37	49.19	9.43	0.81	21.44	2.52	3.27	99.03	3.03	51.1
	A_3	5.20	11.65	49.87	11.11	0.90	20.83	2.80	3.10	100.26	3.04	48.5

illite contains 6 per cent K_2O, the illite content of the samples varies from 37 to 58 per cent. The SiO_2: R_2O_3 ratios, while not being reliable criteria for identification, do point toward 2 : 1 layer lattice minerals rather than to kaolinitic minerals. The base exchange values are fairly high and are higher than would be expected if kaolinite were present in very large amounts.

Illite has approximately one-half the base exchange capacity of montmorillonite. It contains fixed potassium to about twice the value of its own base exchange value. The importance of the fixed potassium in satisfying the lattice charges in the illites is thus apparent when it approaches or exceeds the base exchange value in satisfying the lattice charges. It indicates either:

(*a*) a mixture of illite and montmorillonite, or

(*b*) a mineral intermediate in properties between illite and montmorillonite.

Table 3 shows the mineral formulae as calculated by the method of Ross and Hendricks (18) from the data in Table 2.

TABLE 3.—CALCULATED MINERALOGICAL FORMULAE OF THE < 0.001 MM. CLAY FRACTION OF SOIL SAMPLES

Profile	Horizon	Tetrahedral co-ordination		Octahedral co-ordination				Fixed potassium	B.E.C. calculated	B.E.C. observed
		Si^{4+}	Al^{3+}	Al^{3+}	Fe^{3+}	Mg^{2+}	Total			
Waitville	A_1	3.37	0.63	1.38	0.56	0.30	2.24	—	0.21	0.20
	A_2	3.43	0.57	1.27	0.59	0.27	2.13	0.24	0.21	0.19
	B	3.46	0.54	1.23	0.64	0.27	2.14	0.21	0.18	0.18
	B(ca)	3.49	0.51	1.25	0.54	0.34	2.13	0.23	0.23	0.22
	C	3.59	0.41	1.18	0.55	0.38	2.11	0.23	0.23	0.21
Melfort	A	3.67	0.33	1.33	0.50	0.30	2.13	0.23	0.24	0.22
	B_1	3.74	0.26	1.23	0.59	0.28	2.10	—	—	—
	G	3.48	0.52	1.23	0.55	0.37	2.15	0.24	0.20	0.21
	C	3.52	0.48	1.37	0.48	0.29	2.14	0.23	0.21	0.21
Regina	A	3.55	0.45	1.35	0.46	0.27	2.08	0.23	0.23	0.21
	B_1	3.56	0.44	1.28	0.45	0.39	2.12	0.24	0.23	0.24
	B^2	3.51	0.49	1.27	0.48	0.37	2.12	0.26	0.24	0.25
	C	3.50	0.50	1.38	0.44	0.32	2.14	0.22	0.18	0.18
Val Marie	A saline	3.51	0.49	1.17	0.62	0.33	2.12	0.25	0.21	0.23
	B-C	3.67	0.33	1.23	0.50	0.34	2.07	0.22	0.24	0.24
	A	3.65	0.35	1.27	0.50	0.28	2.05	0.21	0.27	0.25
Sceptre	A	3.59	0.41	1.32	0.44	0.41	2.17	0.21	0.23	0.23
Echo	B_1	3.55	0.45	1.26	0.58	0.27	2.11	0.20	0.19	0.18
	B_2	3.53	0.47	1.28	0.56	0.31	2.15	0.17	0.16	0.16
	B(ca)	3.53	0.47	1.21	0.54	0.39	2.14	0.25	0.19	0.18
	C	3.57	0.43	1.28	0.53	0.30	2.11	0.19	0.21	0.21
Estevan	C	3.42	0.58	1.12	0.56	0.52	2.20	0.25	0.25	0.25
Trossachs	A	3.52	0.38	1.33	0.43	0.28	2.04	0.32	0.22	0.21
	A_2	3.51	0.49	1.31	0.50	0.27	2.08	0.30	0.22	0.22
	A_3	3.50	0.50	1.22	0.59	0.29	2.10	0.28	0.19	0.21

The data in Table 3 show that the mineralogical formulae are all very similar. The silicon in tetrahedral co-ordination varies between 3.37 and 3.74 with an average of 3.54. This is about midway between the montmorillonite and beidellite ends of the montmorillonite-beidellite series. The number of ions in octahedral co-ordination averages 2.15 which is closer to beidellite than to montmorillonite. This does not preclude the occurrence of illite. Ross and Hendricks (18) say "as beidellite is approached there is a decided tendency toward the formation of mixed layer type minerals containing potassium".

The mineralogical formulae thus indicate that the clay from the different samples is very similar, that it is approaching beidellite in the montmorillonite-beidellite series and that there is a strong probability that mixed layer type minerals containing potassium are present.

X-ray Analysis

The X-ray powder diffraction data are given in Figure 1. The diffraction patterns were, in general, very weak so that it was not possible to obtain positives from them. The wide interplanar spacings only were used

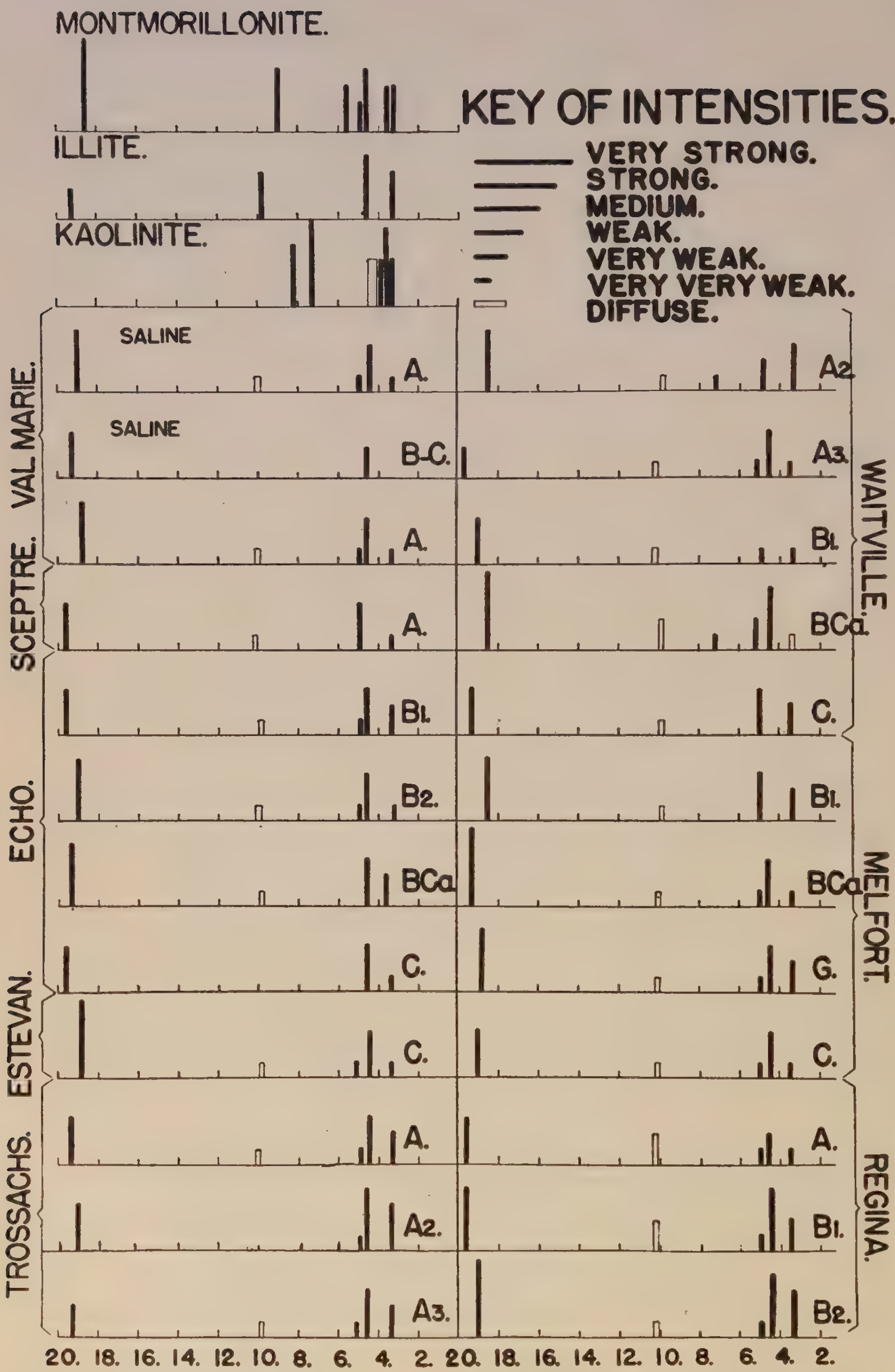

FIGURE 1. Interplanar spacing of clay minerals and of the < 0.001 mm. fraction clay of soil samples by X-ray diffraction analysis.

for identification purposes as recommended by Kelley *et al.* (14), that is, the 18.5 + A° for montmorillonite, the 10 A° for illite and 7.2 A° for kaolinite.

From Figure 1 it is seen that kaolinite appears only in the A_2 and the B(ca) horizons of the Waitville profile and the intensity in both cases is very weak. As the reference sample of kaolinite gave a very strong line at 7.2 A° the amount of kaolinite in these two samples is very small. In the other samples it is probably absent but if present it must be a very minor constituent.

Montmorillonite is present in all samples but the intensity of the montmorillonite line varies from strong to very weak. Most samples have medium or weak lines, indicative of a fair amount of montmorillonite being present. As no dilutions were X-rayed for standards, no estimation of the amount of montmorillonite present in the samples is made.

Illite is shown to be present in all samples except the B-C horizon of the Val Marie profile and the C horizon of the Echo profile. The intensity of the 10 A° line in practically all samples is very, very weak, and the line is diffuse. Hellman *et al.* (10) suggest that up to 40 per cent illite may be overlooked by the X-ray method so that the faint lines recorded may represent 40 per cent or more illite. The B-C horizon of the Val Marie and the C horizon of the Echo profiles contained less K_2O than the other samples suggesting less illite. The illite in these two samples may have been missed by the X-ray method.

Quartz is present in all samples as shown by the 3.34 A° diffraction line. This line is weak and it is thought that the amount of free silica in these samples was small.

Differential Thermal Analysis

The differential thermal analysis curves are given in Figure 2. The curves for the reference materials are in good agreement with the curves for similar materials published by various investigators.

In the curves for the soil clay fractions, an endothermic peak occurs about 130° C., a second endothermic peak at about 535° C. and a third small endothermic peak about 875° C., followed immediately by a small exothermic peak. In several samples an exothermic effect occurs between 200° and 400° C. which is considered to be due to a slight amount of organic matter remaining in the sample.

The magnitude of the low-temperature endothermic effect varies greatly. As no attempt was made to treat the samples identically as far as moisture was concerned, large differences in the magnitude of this curve would be expected. This endothermic effect is of no particular use in identification, as pointed out by Barshad (2).

The peak at about 535° C. is remarkably uniform for all samples. A peak at this temperature could be due to montmorillonite, illite and kaolinite. However, if kaolinite were present to the extent of 5 per cent (8) an exothermic peak at 980° C. would be shown. As there is no peak at this temperature, kaolinite may be considered to be absent, or if present, to be in very minor amounts. The 535° C. peak could be due to montmorillonite

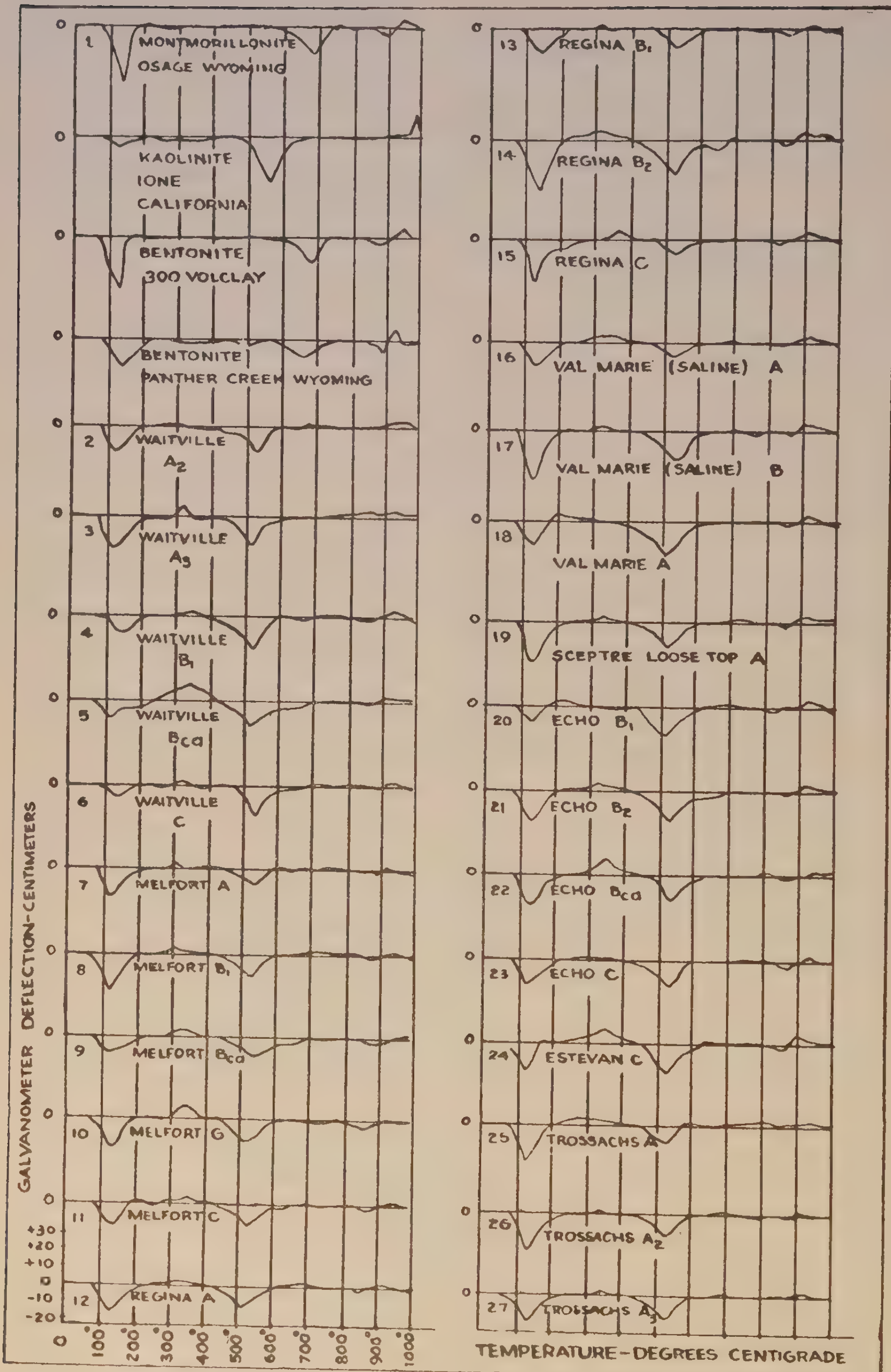

FIGURE 2. Differential thermal analysis curves of clay minerals and of the < 0.001mm. fraction clay of soil samples.

containing a high proportion of iron in the lattice, or it could also be due to illite which also gives a peak in this range. The peak could also result from a mixture of montmorillonite and illite.

The small endothermic peak at about 875° C., followed immediately by a small exothermic peak, is characteristic of the 2 : 1 layer lattice minerals. As both montmorillonite and illite give this reaction, this peak cannot differentiate them. It does further indicate that the soil clays contain predominantly 2 : 1 layer lattice clay minerals.

The curves are very uniform for all the soil clay samples. This indicates a similarity of mineralogical constitution (19). The curves are well defined and sharp, indicating that there is probably only a small percentage of amorphous material.

DISCUSSION AND CONCLUSIONS

The above results are in keeping with published literature on the formation and occurrence of the clay minerals. Kaolinite is usually found in the clay fraction of highly weathered soils formed in warm, humid climatic regions (6, 7, 18).

Grim (7) considers that minerals of the montmorillonite type tend to form under cooler conditions and occur as residual weathering products. Ross and Hendricks (18) report that the grasslands of Canada contain large areas where montmorillonite is a prominent constituent of the clay fraction. They consider that beidellite with a high content of ferric iron is the predominant mineral of this soil and that these clays may contain mixed layers of mica and other minerals of similar character.

Illites are the prime constituents of many shales (7) and in Canada, in places, there are glacial accumulations of much ground crystalline rock and re-worked shale which originally contained minerals of the hydrous mica type. Larson *et al.* (15), investigating soils produced by weathering of calcareous till under Eastern Nebraska conditions, found that iron-rich montmorillonite or illite was the dominant clay mineral. They found no evidence of segregation of any type of clay mineral during the formation of the B horizon and that the nature of the clay had not been materially changed during soil formation.

Since Saskatchewan soils are not highly weathered and the climate is cool, kaolinite would not be expected to be found as the dominant clay mineral in the clay fraction of these soils, except, perhaps, in grey wooded (podzolic) soils which are more highly weathered. These soils are of glacial origin and contain mixed rock and shales, so that montmorillonite and illite would be expected to be the dominant clay minerals.

Chemical analyses indicate that the clay minerals, in this clay fraction of the soil samples, fit best a 2 : 1 layer lattice mineral. The base exchange values are too high for the clay samples to contain large amounts of kaolinite. The conclusion on the basis of fixed potassium is that the clays contain about 45 per cent illite assuming an average of 6 per cent K_2O for illite. From chemical analysis and the mineralogical formulae calculated from the analytical data the clays are shown to be very similar, to be composed of either montmorillonite-beidellite mixed with illite, or of species intermediate between these types.

The X-ray diffraction data show essentially the same, with definite signs of illite and expanding lattice minerals, either montmorillonite or beidellite, but no kaolinite except in two separated horizons of the podzol profile where traces were indicated.

The differential thermal analysis indicates the presence of 2 : 1 layer minerals, unidentifiable as to type, and again, no kaolinite. The test, being positive and sensitive to kaolinite, demonstrates the negligible place of kaolinite in these soils as a product of weathering.

There is no great variation within profiles or between profiles. Thus, neither weathering nor type of vegetation appears to have affected the composition of the clays, as the clay from the upper horizons is of the same mineralogical composition as the parent material. A trace of kaolinite was found by X-ray diffraction in the podzolized horison and in the lime layer of the podzol profile but thermal analysis did not confirm the presence of kaolinite in these samples. There is no satisfactory evidence for the existence of kaolinite in Saskatchewan soils, even under podzolic weathering.

This study indicates that the clay minerals in the < 0.001 mm. fraction of Saskatchewan soils are very similar and that they are roughly a mixture of about equal parts montmorillonite-beidellite and illite.

SUMMARY

The clay fraction of the < 0.001 mm. effective diameter was separated from the horizons of several Saskatchewan soil profiles, representing soils from different soil zones and soil associations. Detailed chemical analyses, X-ray powder diffraction analysis, and differential thermal analysis methods were used in identifying the clay minerals present. The three methods all indicated that kaolinite was absent, and that the clay minerals present were of 2 : 1 layer lattice type. From chemical analysis, based on fixed potassium, about 45 per cent of the clay fraction is considered to be illite with the remainder montmorillonite-beidellite. Indications are that all profiles studied and all samples within the profiles were very similar in clay mineral composition and that the weathering conditions and type of vegetation represented have produced no significant differences in the resulting clay minerals. The mineralogical nature of the clay fractions of Saskatchewan soils seems to be very similar to that of the parent material and is probably inherited from shales which have been important as sources of Saskatchewan soils.

ACKNOWLEDGMENTS

The authors wish to acknowledge with appreciation the assistance given by W. G. Worcester and W. Phipps of the Ceramics Department, University of Saskatchewan, for making the furnace for the differential thermal apparatus; to J. L. Doughty, Officer-in-Charge, Soil Research Laboratory, Swift Current for helpful criticism of the manuscript and for making available space and equipment for part of the analytical work, and to J. Mitchell, Professor of Soils, University of Saskatchewan, for helpful guidance and encouragement during this investigation.

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RESPONSE OF BROMEGRASS TO NITROGEN FERTILIZERS[1]

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The use of nitrogen fertilizers to increase forage and seed production of perennial grasses is becoming increasingly widespread in Europe and the United States. In Western Canada, however, the use of nitrogen fertilizers has not been extensive. This paper presents results of preliminary tests of nitrogen fertilizers on bromegrass in two districts of Saskatchewan. These studies indicate that moisture conditions and time of fertilizer application are important factors to be considered in the recommendation of nitrogen fertilizers for grasses in this region.

LITERATURE REVIEW

Marked increases in forage and seed production of bromegrass following the use of nitrogen fertilizers were reported by Harrison and Crawford (5) in Michigan, Anderson *et al.* (1) in Kansas, Bourg *et al.* (2) in Nebraska, Metcalfe (8) in Iowa, and Klages and Stark (6) in Idaho. Evans and Wilsie (3) and Newell (9) also found nitrogen supplements to have an important bearing on growth and flowering of bromegrass under greenhouse conditions. In Eastern Canada Fulkerson *et al.* (4) found a variable response in seed yields for seven perennial grasses following applications of nitrogen fertilizers. MacVicar and Gibson (7) found rate of nitrogen fertilization more important than kind of fertilizer in increasing seed production of orchard grass.

MATERIALS AND METHODS

All tests were conducted on well established seed fields of farm cooperators. Most of the tests were in a concentrated seed production area around Unity and Wilkie in west-central Saskatchewan on sandy loam and loam soils of the dark brown soils zone. A single test was made at Melfort, Saskatchewan, in the black soils belt. The soil in this test was a silty clay loam. Age of bromegrass stands which were used for testing varied from three to nine years and fields were considered by the seed growers to have reached a sod-bound or declining state of production. No previous fertilization had been given.

From 1947 to 1949 the paired plot type of test was used. Fertilized and unfertilized strips were 11 feet wide and 100 to 200 feet long. In later trials randomized block tests with four to six replications and plots 11′ × 50′ were employed. Fertilizers were applied to the surface of the soil by hand or with a Cyclone seeder. Rates of application were on the basis of pounds of elemental nitrogen per acre. Fertilizers used were ammonium sulphate (21 per cent nitogen), ammonium nitrate (33.5 per cent nitrogen), and ammonium phosphate 16-20 (16 per cent nitrogen). From 1947 to 1950 hay yields were taken as the total weight of straw and seed at seed harvest

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time. In 1951 separate cuttings were made at appropriate times for hay and seed yield determinations. Square yard areas were cut by hand for yield determinations with 10 samples being taken from each plot of fertilized and unfertilized strips of paired plot tests and three to four samples from plots of randomized block tests.

RESULTS

In preliminary trials in the Unity area in 1947 and 1949 very unsatisfactory responses to nitrogen fertilizers were obtained (Table 1). Drought conditions prevailed in this area in both years and as a result there was little growth on unfertilized or fertilized plots.

TABLE 1.—EFFECT OF AMMONIUM SULPHATE FERTILIZER ON FORAGE AND SEED YIELDS OF BROMEGRASS, UNITY, SASK. RESULTS ARE AVERAGES OF 5 TESTS 1947 AND 4 TESTS 1949. FERTILIZERS WERE APPLIED APRIL 28, 1947 AND OCTOBER 28, 1948

Rate of fertilization—lb. nitrogen per acre	Hay yield—tons per acre		Seed yield—lb. per acre	
	1947	1949	1947	1949
0	0.2	0.2	15	55
20	—	0.3	—	76
40	0.3	0.4	29	74
80	0.3	0.5	17	76

More extensive trials were carried out in this area in 1950 and 1951. Quite favourable moisture conditions prevailed in these years and good responses to fertilizers were obtained (Tables 2 and 3).

Significant increases in hay production were obtained in both 1950 and 1951. Yields of hay increased with increasing rates of nitrogen application up to and including the 80 lb.-per-acre rate. Fall applications gave slightly higher hay yields than spring fertilization but the differences were not significant. Striking increases in seed production were obtained from fall applications of fertilizer. The greatest increase in seed yield was 209 pounds per acre in 1951 following the use of 80 pounds of nitrogen per

TABLE 2.—EFFECT OF NITROGEN FERTILIZERS ON FORAGE AND SEED PRODUCTION OF BROMEGRASS 1950. YIELDS ARE AVERAGES FOR SIX FARMS IN THE UNITY-WILKIE AREA OF SASKATCHEWAN

Treatment	Rate of fertilization*	Time of fertilization	Hay—tons per acre	Seed—lb. per acre
Check	0	Oct. 4, 1949	0.7	92
Ammonium sulphate	20	Oct. 4, 1949	1.0	115
Ammonium sulphate	40	Oct. 4, 1949	1.2	145
Ammonium sulphate	80	Oct. 4, 1949	1.7	147
Ammonium sulphate	40	April 24, 1950	1.2	107
Ammonium nitrate	40	April 24, 1950	1.4	92
L.S.D. (P = 0.05)	—	—	0.2	31

* Pounds of elemental nitrogen per acre.

TABLE 3.—EFFECT OF NITROGEN FERTILIZERS ON FORAGE AND SEED PRODUCTION OF BROMEGRASS 1951. YIELDS ARE AVERAGES FOR 5 FARMS IN THE UNITY-WILKIE AREA OF SASKATCHEWAN

Treatment	Rate of fertilization*	Time of fertilization	Hay—tons per acre	Seed—lb. per acre
Check	0	—	1.4	92
Ammonium nitrate	20	Sept. 22, 1950	2.2	153
Ammonium nitrate	40	Sept. 22, 1950	2.8	225
Ammonium nitrate	80	Sept. 22, 1950	3.2	301
Ammonium nitrate	40	May 6, 1951	2.6	135
Ammonium sulphate	40	Sept. 22, 1950	2.6	194
Ammonium sulphate	40	May 6, 1951	2.6	116
L.S.D. ($P = 0.05$)	—	—	0.2	24

* Pounds of elemental nitrogen per acre.

acre. Spring fertilization was much less effective than early fall applications in increasing seed yields. Ammonium nitrate appeared somewhat preferable to ammonium sulphate for the stimulation of both hay and seed production.

Two of the five tests in 1951 in the Unity-Wilkie area were on sandy loam soils and three were on loam soils. Average forage yields were similar for both soils and equal increases in forage yields were obtained following fertilization. Seed yields, however, were increased considerably more following fertilization of sandy textured soils than of the loam soils. Seed yields averaged 101 pounds and 85 pounds per acre for untreated plots of sandy and loam soils respectively. Average yields for all fall fertilized plots were 286 pounds per acre for the sandy soils and 172 pounds per acre for loam soils. It would appear that fertilizer applications may be much more effective on lighter textured soils providing moisture conditions are favourable.

The marked differential forage and seed response of bromegrass to season of application is shown further in a test at one location in the Unity area in 1951 (Table 4). This six-replicate test compared three nitrogen carrying fertilizers and four dates of fertilizer application. The low seed yields of this test resulted from hail damage between the time of hay and seed harvest.

As shown in Table 4 hay yields varied little for different times of fertilizer application or types of fertilizer. Seed production, however, was highest for the August application and showed progressive reductions as the time of application was delayed. For seed production ammonium nitrate was superior to ammonium sulphate both when the fertilizer was applied in the fall and in the spring. Ammonium phosphate gave somewhat poorer forage responses than ammonium nitrate or ammonium sulphate but seed yields were similar for all three fertilizers.

The test at Melfort in the black soil zone consisted of a comparison of ammonium nitrate and ammonium sulphate fertilizers applied at four rates. Fertilizers were all applied May 10, 1950. Yields of hay and seed were taken in 1950 and again in 1951 to obtain residual effects from 1950 treatments. Table 5 presents a summary of hay and seed yields for this test.

TABLE 4.—EFFECT OF NITROGEN FERTILIZERS ON FORAGE AND SEED PRODUCTION OF BROMEGRASS 1951, SINGLE FARM UNITY, SASK. ALL TREATMENTS PROVIDED 40 POUNDS OF ELEMENTAL NITROGEN PER ACRE

Kind of fertilizer	Seed and hay yields following fertilizer applications made				
	Aug. 24, 1950	Sept. 21, 1950	Nov. 3, 1950	May 6, 1951	Check—not fertilized
		Hay yields in tons per acre*			
Ammonium nitrate	3.0	3.1	2.9	2.9	—
Ammonium sulphate	3.2	2.9	2.9	2.9	—
Ammonium phosphate	—	—	2.4	2.7	—
Average A.N. and A.S.	3.1	3.0	2.9	2.9	1.8
		Seed yields in lb. per acre**			
Ammonium nitrate	93	56	46	38	—
Ammonium sulphate	81	52	42	28	—
Ammonium phosphate	—	—	40	32	—
Average A.N. and A.S.	87	59	44	33	28

* L.S.D. (P = 0.05) equals 0.4 tons per acre.
** L.S.D. (P = 0.05) equals 25 pounds per acre.

TABLE 5.—EFFECT OF NITROGEN FERTILIZERS ON FORAGE AND SEED YIELDS OF BROMEGRASS, MELFORT, SASK., 1950-51

Treatment	Rate of application*	Yield per acre					
		Hay—tons			Seed—lb.		
		1950	1951	Total	1950	1951	Total
Check	—	0.5	0.4	0.9	87	31	118
Ammonium nitrate	20	0.8	0.4	1.2	138	39	177
Ammonium nitrate	40	1.0	0.6	1.7	190	61	251
Ammonium nitrate	80	1.7	1.0	2.7	225	183	408
Ammonium nitrate	160	2.0	1.8	3.8	281	280	561
Ammonium sulphate	20	0.7	0.3	1.0	123	37	160
Ammonium sulphate	40	0.9	0.4	1.4	162	94	256
Ammonium sulphate	80	1.3	0.9	2.2	192	162	354
Ammonium sulphate	160	1.5	1.4	2.9	250	220	470
L.S.D. (= 0.05)	—	0.3	0.7	—	37	89	—

* Pounds of elemental nitrogen per acre.

This test is of interest as it showed marked responses in seed production from spring fertilization and also marked residual effects. On the basis of 1950 results the 160-pound rate of application was little better than the 80-pound rate. However, in view of the residual effects noted in 1951 following the 160-pound rate of application it appears that progressive increases in seed yields are possible up to the 160-pound rate of fertilization. Ammonium nitrate was more effective than ammonium sulphate as a fertilizer both for seed and forage production.

DISCUSSION

The assurance of good moisture conditions is a primary factor to be considered when fertilization of bromegrass is contemplated. In 1947 and 1949 in the Unity seed growing area spring growth of bromegrass was limited by drought and fertilizers were of little value. In 1950 and 1951 with good moisture conditions rather striking results were obtained. Use of high nitrogen fertilizers in the dark brown and brown soil zones consequently is hazardous but they might be used to advantage when there is good fall moisture or if there is an opportunity of using spring run-off moisture or other sources of water. In the black and degraded black soil zones where better moisture conditions prevail the use of nitrogen fertilizers on bromegrass appears to have more general application.

Cost of fertilizer and the value of the crop product are important factors determining the economic feasibility of fertilizer use. Present prices of \$87.50 and \$67.00 per ton for ammonium nitrate and ammonium sulphate, respectively (f.o.b. Saskatoon, Sask.) represent costs per pound of nitrogen of 13.0 ¢ and 16.0 ¢, respectively. Ammonium nitrate is consequently a cheaper source of nitrogen as well as giving better responses on the basis of equal rates of nitrogen application. Table 6 presents a summary of fertilizer costs for different rates of ammonium nitrate application and the increases in yields of forage and seed obtained from the more favourable tests included in these studies. Assuming a farm value of seed of 10 ¢ per pound and a hay value of \$10.00 per ton, it may be seen from Table 6 that the increased yields of seed or hay represent monetary values considerably above the cost of fertilizer. Where the seed can be marketed and the straw sold or fed on the farm the financial gain from the use of nitrogen fertilizers is considerable.

TABLE 6.—COST PER ACRE OF AMMONIUM NITRATE FERTILIZER AT SASKATOON, SASK., 1951 AND INCREASES IN HAY AND SEED YIELDS OF FERTILIZED BROMEGRASS OVER YIELDS FROM UNFERTILIZED AREAS

Rate of application*	Cost per acre ammonium nitrate	Increase in yield, Unity-Wilkie tests, 1951		Increase in yield, Melfort test, 1950-51	
		Hay—tons	Seed—lb.	Hay—tons	Seed—lb.
20	\$ 2.61	0.8	61	0.4	59
40	5.22	1.4	133	0.8	133
80	10.44	1.8	209	1.9	290
160	20.88	—	—	3.0	443

* Pounds elemental nitrogen per acre.

Most suitable rates of application of nitrogen fertilizers also may be obtained from a consideration of Table 6. For the Unity-Wilkie tests seed yield increases were proportional for the 20- and 40-pound rates of nitrogen but declined for the 80-pound rate. In the Melfort test the rate of seed yield increase continued to the 80-pound rate and declined somewhat for the 160-pound rate. The greatest increase in forage production

per pound of fertilizer applied was shown for the 20-pound rate in the Unity-Wilkie tests and for the 80-pound rate in the Melfort trial. Considering both seed and forage production it would appear that rates of over 40 pounds of nitrogen per acre should be recommended only under very favourable moisture conditions.

Where forage production alone is wanted spring applications or late fall applications appear as useful as early fall applications. When seed production is intended August or September application would seem desirable. The greater effect of early fall applications on seed production may well be related to plant growth in the fall. It was observed that early fall applications resulted in considerably more leaf development which remained green later in the fall than the growth of unfertilized areas. Marked residual effects noted in the Melfort trial following spring application may have resulted from too late an application for full utilization by the first crop. The carryover then encouraged fall development and stimulation of seed production the next season. Residual effects of this type have been observed at Saskatoon following spring applications of fertilizer to Russian wild rye grass. This species makes very rapid spring growth and matures seed in mid-July. Effects of spring fertilization on seed production of this grass have been greater in the year following application than in the year of application.

SUMMARY

1. Spring and fall applications of nitrogen fertilizers to bromegrass resulted in unsatisfactory stimulation of forage growth and seed production in years of limited rainfall.

2. Under favourable moisture conditions nitrogen fertilizers resulted in increased hay yields of over one ton per acre and increased seed yields of over 100 pounds per acre.

3. August or September fertilizations were more satifactory than late fall or early spring treatments in stimulating seed production. Hay yields were increased only slightly more by fall application than by early spring applications.

4. Ammonium nitrate was preferable as a source of nitrogen to ammonium sulphate both with regard to response per pound of nitrogen applied and cost per acre. No yield responses to phosphorus were obtained.

5. Most satisfactory rates of application were 40 pounds of nitrogen per acre for tests in open-prairie areas and 80 pounds per acre for the single test in the park belt.

ACKNOWLEDGMENTS

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Unfortunately, the title and authors of one of the papers published in the September, 1952, issue of "Scientific Agriculture" were omitted from the front cover. The "*Contents*" for September should have included:

EFFECT OF CROPPING SYSTEMS ON THE AGGREGATION OF A BROOKSTON CLAY SOIL AT THREE DEPTHS[1]

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[Received for publication April 9, 1952]

Aggregation has been used as a measure of the physical condition of a soil (1, 3). The improved soil structure resulting from greater aggregation is usually manifested in better air-water relationships of the soil and increased crop yields. An increase in the aggregation may not only lower the bulk density and increase total and non-capillary porosity, but the size and the distribution of the soil pores are usually affected in such a way as to bring about an increase in percolation, hence improved drainage.

The extent to which a soil is aggregated may be determined by various physical means in the laboratory, and the results expressed in various ways. A common means of determining soil aggregation is by the Yoder wet-sieving technique (7). This method involves the agitation of a soil sample in water at a constant rate for a definite time-interval on a nest of sieves of decreasing opening size. The sample fractions left on the various screens at the end of this agitation interval are oven-dried and weighed. The primary particles are removed. The results may be expressed as a coefficient of aggregation, which is a measure of the surface area presented by the water-stable aggregates of the soil sample. A poorly aggregated soil will have a low coefficient of aggregation, whereas a well aggregated sample will yield a higher value.

The present study was carried out to investigate the effects of certain cropping systems upon aggregation at different depths on Brookston clay. This soil type is widely distributed in Kent and Essex Counties (5) and is of considerable agronomic importance in the production of high-value cash crops such as corn and soybeans. Recent crop yields have shown a marked decline where these cash crops have been grown continuously for many years (4).

The Brookston series exhibits the characteristics of Dark Grey Gleisolic soils (5). The parent material is classed as a heavy ground moraine altered by wave action and lacustrine deposits. Under natural conditions the drainage is very slow, being inhibited by the compact and relatively impervious subsoil. When continuous cropping with corn or soybeans is practised, the soil structure is impaired and the natural drainage is believed to be further restricted.

This study attempted to investigate the differences in aggregation brought about by two extreme cropping practices and by a cropping system considered to be favourable in effect. The practices selected as extremes included an area of clipped bluegrass sod which had remained as such for approximately 50 years, and plots of continuous corn situated on land reputed to have been cropped heavily for about 30 years. These sites were

[1] Adapted for publication from a thesis submitted to the Graduate School, University of Toronto, by E. F. Bolton, in partial fulfilment of the requirements for the degree of Master of Science in Agriculture.

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chosen so that a portion of another system might be compared with them in aggregating ability. This system was a 5-year rotation consisting of corn, corn, oats seeded down, alfalfa-brome and alfalfa-brome. All phases of this rotation were represented each year, so that it was possible to make a simultaneous examination of the aggregation of the soil at the three successive stages of the rotation under study, namely: oats seeded down, alfalfa-brome first year, and alfalfa-brome second year. These crops occurred on land which had been intensively farmed prior to setting up the crop rotation studies. At the time of this study the crops were completing the first cycle of the 5-year rotation, that is, alfalfa-brome second year had been preceded by alfalfa-brome first year, oats seeded down and corn.

EXPERIMENTAL PROCEDURE

Unfertilized rotation plots on the Dominion Experimental Sub-station, Woodslee, were selected as representative of the Brookston soil. Soil samples were taken by spade at three depths from the plots of continuous corn, oats, alfalfa-brome first year, alfalfa-brome second year, and from a bluegrass sod area.

The cropping treatments appeared in duplicate, although they were not arranged in the conventional blocks, for purposes of error control. However, it was considered feasible to apply the analysis of variance to the data since there were no differences in per cent clay content between plots.

For the aggregation determination, two samples were taken from each plot and each sample was analysed in duplicate in the laboratory. The four values thus obtained for each plot were averaged and this average value used for statistical analysis. The samples were analysed by the Yoder wet-sieving technique (7), the primary particles removed and the results expressed as coefficients of aggregation (3). The size of sample used was equivalent to 50 grams of oven-dried soil.

The per cent organic matter in the samples was determined by the Walkley method (6). The value for each depth and treatment was derived from the mean of four samples analysed in duplicate.

The per cent clay, two microns and less, was determined by the Bouyoucos method (2), with each recorded mean being comprised of four determinations.

EXPERIMENTAL RESULTS AND DISCUSSION

In Table 1 will be found the coefficients of aggregation, per cent organic matter and the per cent clay, two microns and less. This table is divided into three sections corresponding to the three depths of sampling.

Aggregation

In the 0-4 inch layer some crops produced a marked influence on aggregation. The bluegrass sod and alfalfa-brome first and second year plots gave significantly greater soil aggregation values than the continuous corn or the oat plots. The data indicate that the influence on aggregation of the cropping systems studied increased aggregation at the 0-4 inch depth in the order of bluegrass sod > alfalfa-brome (second year) > alfalfa-brome (first year) > oats > continuous corn. As was pointed out above, the oats and the alfalfa-brome crops occurred on soil which had been in

TABLE 1.—COEFFICIENTS OF AGGREGATION, PER CENT ORGANIC MATTER AND PER CENT CLAY FOR CROPPING SYSTEMS AT THREE DEPTHS

Cropping systems	Coefficient of aggregation, mean of 8 determinations	Per cent organic matter, mean of 8 determinations	Per cent clay (2u and less), mean of 4 determinations
	0-4 inch depth		
Continuous corn	297	3.7	34.6
Bluegrass sod	834	8.1	33.3
Oats	370	4.4	37.3
Alfalfa-brome 1st year	512	4.4	36.6
Alfalfa-brome 2nd year	518	5.0	42.3
L.S.D. (0.05)	104	1.06	N.S.
(0.01)	149	1.47	N.S.
	4-8 inch depth		
Continuous corn	430	2.4	37.9
Bluegrass sod	746	4.3	38.8
Oats	526	4.0	41.4
Alfalfa-brome 1st year	662	4.2	37.9
Alfalfa-brome 2nd year	506	4.7	42.3
L.S.D. (0.05)	231	0.92	N.S.
(0.01)	332	1.27	N.S.
	8-12 inch depth		
Continuous corn	517	1.0	45.0
Bluegrass sod	961	1.7	43.6
Oats	611	1.6	47.3
Alfalfa-brome 1st year	720	1.8	40.9
Alfalfa-brome 2nd year	599	2.2	49.1
L.S.D. (0.05)	355	N.S.	N.S.
(0.01)	510	N.S.	N.S.

corn for a number of years. The results for the oats and alfalfa-brome crops suggest an improving effect on aggregation where grass and legumes occur in the system.

At the 4-8 inch depth the bluegrass sod and the continuous corn plots showed extreme effects on aggregation. Alfalfa-brome second year and oats failed to aggregate the soil more than continuous corn. Aggregation in the first year alfalfa-brome plots and under bluegrass sod was significantly greater than in continuous corn plots.

The results at the 8-12 inch depth have failed to reflect any significant trend where the cropping rotation was concerned, but did show an aggregation increase in favour of bluegrass.

Organic Matter

In all cases the per cent organic matter decreased with depth but at the 8-12 inch depth the content according to crop was not significantly different. While the organic matter increases arising from the alfalfa-brome mixtures were not significant, the trend may support a recommendation for including deep-rooted legumes in a rotation on a Brookston clay soil.

Organic matter had a high correlation value (r = 0.95) at the 0-4 inch depth with aggregation. At the two lower depths organic matter failed to show a significant correlative value with the coefficient of aggregation.

Clay Content

The differences in clay content were not significant in any plot at the same depth. The data would suggest that the clay content might not account for the different aggregation values according to crops.

The Brookston clay is classed as a poorly drained soil under natural conditions. Despite the restricted movement of water, there has been an increase in clay content in each plot at the 8-12 inch depth.

SUMMARY

Aggregation determinations were made on Brookston clay soil samples from the plots of the Dominion Experimental Sub-station, Woodslee. Continuous corn, oats, alfalfa-brome (first and second year) plots, and bluegrass sod were sampled at three depths. The results were expressed as coefficients of aggregation.

Results at the 0-4 inch depth were markedly influenced by the cropping system. The crops may be arranged in a decreasing order of aggregating effect: bluegrass sod > alfalfa-brome (second year) > alfalfa-brome (first year) > oats > continuous corn. Those crops that tend to add organic matter had a favourable effect on aggregation.

Organic matter decreased with depth, the actual percentage depending on the cropping system. Those plots under corn had the lowest values while alfalfa-brome (second year) plots had more organic matter at the two lower depths than bluegrass sod, but these differences were not significant.

There was a noticeable increase in clay content with depth despite the relatively low permeability rates of the Brookston clay.

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